Krispijn te Riet

Contracting RTA Time Windows for Cost Efficient Aircraft Arrival Scheduling

TU Delft

Contracting RTA Time Windows for Cost Efficient Aircraft Arrival Scheduling

By

Krispijn te Riet

in partial fulfilment of the requirements for the degree of

Master of Science
in Aerospace Engineering

at the Delft University of Technology

Supervisors: dr. M. Mitici
Ir. R. Verbeek

This thesis is confidential and cannot be made public.

Preface

To whom it may concern,

One of the primary pursuits in a lot of research in the field of aerospace engineering in general, but airline operations in particular, is the increase of efficiency and the intertwined reduction of spillage. These types of research are frequently put in a context of sustainability in environmental terms: Quieter engines reduce the effect of sound pollution around an airport and more efficient aircraft reduce the emission of greenhouse gasses. One aspect of sustainability in the aviation industry is however overlooked too often. This is the sustainability of the aviation industry itself.

Since the 1973 and 1979 energy crises profit margins in the aviation industry have come under big pressure. This pressure resulted from both external forces, like increasing fuel prices, and internal factors like the emergence of budget carriers. To preserve the existence - and convenience - of air travel as we know it, I think it is necessary to put more emphasis in research and innovation on the financial and economic aspects. Therefore, this research will focus on these topics.

When I first read the MSc graduation assignment (which can be found in Appendix B), I thought it could put important steps to increase the profitability for airlines from an ATM perspective. For these reasons I focussed the research on sustainability in economic terms. Arguably, the findings of the research can be used to state that the developed methodology can reduce the environmental impact of aviation, but I think this is of secondary importance.

Besides justifying the approach I have taken I would also like to use this preface to express my gratitude to those who have had a positive contribution to this research. This is definitely not limited to those who have had a contribution to the content. I would therefore like to especially mention my family and friends who have done a great deal in motivating me over the coarse of the project.

I wish those who read this a happy and insightful read, and I sincerely hope that spending the time to read this may be a valuable contribution to your life.

Best regards,

Krispijn te Riet

Abstract

Currently aircraft are scheduled in the latest stages of a flight with a scheme that resembles First Come, First Serve (FCFS). The aircraft land in the order they arrive. If multiple aircraft arrive simultaneously they will be queued to create sufficient separation time between them. This delay has a cost to airlines.

It is proposed that the total cost of the operation of aircraft can be reduced by the employment of a scheduler, over the entire flight duration, that takes into account the uncertainties that arise from weather influences. One way to do so is with the implementation of contracting, dynamic Required Time of Arrival (RTA) windows. It is proposed that if these windows are used aircraft are given more freedom to fly their desired speed, while increasing their separation as they move closer to the airport.

In this thesis a scheduling methodology is developed that makes use of time windows. The developed technique is based on the density of Expected Times of Arrival (ETAs) in these windows to create buffers where necessary. Monte Carlo simulations are performed on a homogeneous aircraft set to assess the performance of the method.

It is shown in the thesis that the developed method can reduce the operational costs for airlines significantly. This is particularly true in situation where many aircraft aim to land close to eachother, i.e. when the runway operates close to its capacity limit.

Contents

1 Introduction **5**

2 Literature Review **7**
- 2.1 Introduction 7
- 2.2 Literature review 7
- 2.3 Results and Analysis 11
- 2.4 Discussion and Conclusions 12

3 Research Plan **13**
- 3.1 Introduction 13
- 3.2 Research question, aims and objectives 14
- 3.3 Methodology 15
- 3.4 Results, Outcome and Relevance 15
- 3.5 Conclusions 15

4 Quantification of Costs **17**
- 4.1 Variable Costs 17
- 4.2 Fuel Costs 18
- 4.3 Total Costs 19

5 Wind Modelling **21**
- 5.1 Real Wind State and Observed Wind State 21
- 5.2 Wind Forecasts 22
- 5.3 Errors in Wind Forecasts 22

6 Model **26**
- 6.1 Assessment of Scheduling Techniques 26
- 6.2 Parameter Definition 27
- 6.3 Cost Function 29
- 6.4 Testing Model Overview 31

7 Scheduling Techniques **33**
- 7.1 Current Scheduling Techniques 33
- 7.2 Simulating FCFS 33
- 7.3 Ration-by-Schedule (RBS) 34
- 7.4 PTAs used to impose RTA restrictions to minimize overall costs 35

8 Results **43**
8.1 Parameter Choices . . . 43
8.2 Results for Differing Capacity Utilization Levels . . . 46
8.3 Sensitivity of DPTA-BS Parameters . . . 50
8.4 Conclusion . . . 53

9 Verification **54**
9.1 Model Verification . . . 54
9.2 Scheduling Algorithm Verification . . . 56

10 Conclusions **59**
10.1 Conclusions . . . 59
10.2 Academic Contribution . . . 60

11 Recommendations **61**

Bibliography **65**

A Numerical Results **66**

B Thesis Assignment **72**

Chapter 1

Introduction

In the current world of aviation aircraft are scheduled in the last stages of a flight according to a method that resembles First Come, First Serve (FCFS). This methodology however has one major flaw: it does not account for the arrival of multiple aircraft at the same time efficiently. In such cases it lets one of the aircraft land first, and delays the others by applying radar vectoring or letting them fly a holding pattern. When this is done aircraft incur costs because of the time delay and the unnecessary burn-off of fuel. It is therefore desirable to have a method that reduces the use of vectoring and holding.

There are already several provisions in place to reduce the workload for air traffic controllers (ATCOs) that also reduce the need for vectoring and holding. The most prevalent of such provisions is the intervention of the Central Flow Management Unit (CFMU) before flights depart. The CFMU delays flights before take-off to prevent congestion in sectors and at airports. Delaying aircraft before take-off is also known as ground holding [1].

Even though ground holding reduces the need for holding and vectoring, primarily for shorter flights, it does not remove it completely. Because the CFMU makes use of a weather forecast to estimate what ground speeds aircraft will by flying at different stages of the flight, the uncertainty the CFMU has to deal with increases as the length of a flight increases. It seems therefore useful to have a methodology that acts on the Estimated Times of Arrival (ETAs) of the aircraft that are to land at an airport while the aircraft are flying. This is known in literature as arrival management. It is intended that speeds are altered during the flights to order aircraft before they get under direct control of the destination airport's ATCOs as such, that holding and vectoring is required in the latter stages of the flight to a limited extent.

It is the intention to have small changes in flight speed over a long time period, to avoid large speed changes for shorter time periods. According to Tielrooij et al. the first approach is preferable over the latter [2].

A promising way to do this seems to be the employment of the Required Time of Arrival (RTA) functionality in the modern Flight Management System (FMS), in a way that is similar to the employment of it in [3] by Klooster et al. Klooster et al. make use of 4D Trajecotry Based Operations (TBO) as point of departure to conclude that the airspace capacity can be increased. Even though their proposal does not directly employ the RTA functionality in the FMS it does include the time control aspect of RTA.

This research aims to extend the methodology of Klooster et al. w.r.t. to account for savings in terms of monetary costs to benefit airlines. This research will develop a methodology that applies dynamic time control windows to the RTA. This is intending to give aircraft more freedom to aircraft in terms of speed in the early stages of the flight, while reducing this freedom as the flight progresses. This idea originated in a thesis by Mitici ([4]) who showed that such a methodology can be fruitful for further research. Her methodology had the intention to give aircraft more freedom to adhere to their scheduled time of arrival at a for them efficient flight speed. If a newly developed methodology is shown to be fruitful it may be implemented in the context of 4D trajectories that was proposed by Klooster et al. in [3].

The objective of the project is threefold: Firstly, a method is to be developed that allows for the efficient control of an aircraft's arrival time within an RTA window. Secondly, a new arrival planning method is to be designed that generates dynamic arrival time windows. Third and last, the newly developed method needs to be compared to currently used arrival planning methods.

To satisfy these objectives the following research question has been formulated: *"How can the efficiency, measured in economic terms as resultant of unnecessary delays and fuel usage, of flights be improved by dynamically controlling the CTA time windows of arriving flights until the initial approach fix, and what is the effect on efficiency?"*

The aforementioned points will be tackled in the following order: Firstly the results from a literature review are presented in chapter 2. A project plan with accompanying research questions is presented in chapter 3. The direct costs of the operations of aircraft are introduced in chapter 4. The effects of errors in wind predictions are introduced in chapter 5. A cost function and testing methodology are introduced in chapter 6. In chapter 7 a new scheduling algorithm is introduced that makes use of the dynamic control of RTA windows. The results wherein a detailed look will be taken at changing utilization levels and a sensitivity study will be performed will be presented in chapter 8. The developed testing model and scheduling algorithm will be verified in chapter 9. The research is concluded in chapter 10. Finally, recommendations for future research and implementation are made in chapter 11.

Chapter 2

Literature Review

2.1 Introduction

Over recent years, especially with the advent of aviation modernisation efforts like SESAR[1] in Europe and NextGEN in Northern America, several old customs are being reviewed. One such custom is the way in which Air Traffic Controllers do their job. Currently, they use a method known as First-Come, First-Serve for scheduling flights for arrival that is not necessarily the most efficient in terms of fuel consumption.

This literature review looks into the topic of Controlled Time of Arrival and Required Time of Arrival for use in arrival schedulers. Specifically, a look is taken at whether there are already possible solutions available in the body of science to make use of dynamically varying arrival time windows to reduce costs for airlines by optimizing control of the flow of flights that are inbound for landing.

Section 2.2 will present a review of currently available literature on the topics at hand. In subsection 2.2.1 the difference between different types of Air Traffic Control will be discussed. Subsection 2.2.2 will discuss Required Time of Arrival functionality as currently present in Flight Management Systems. Subsection 2.2.3 will look into arrival managers and the points that are important in the assessment and development of such managers. In particular, it will be discussed what possibilities are present to make use of dynamically varied arrival time windows in section 2.2.3. Section 2.3 will analyse the findings of the literature review and will look where improvements can be made. Finally, section 2.4 will present the conclusions of this paper and make some recommendations for the further course of action.

2.2 Literature review

A literature review was conducted to investigate whether there are potential ways to improve the way in which aircraft are being scheduled for arrival at an airport. At the moment this is done with making use of information about possible (future) congestion being present at the target airport. This information is present in the form of position information of current inbound aircraft, and their Expected Times of Arrival (ETA). It is

[1] Single European Sky ATM Research

thought that if there is a strong prevalence of one ETA several aircraft can pro-actively increase or decrease their speeds to prevent the need for having holding patterns in the latter stages of a flight, which would have a large cost due to the unnecessary use of fuel. Also, the delays that are resulting from this can imply significant costs. In fact, according to [5] current research indicates that the speeding up of selected aircraft in a congested stream can drastically decrease the overall operation costs, even though some aircraft may be burning more fuel. In fact an overall reduction in fuel usage is expected despite the increase in fuel consumption for these selected aircraft.

2.2.1 Tactical and Strategic Control

The tasks of air traffic management can be split in roughly two different parts, dependent on the aim of each operation. The first part is strategic control that is typically done in a Central Flow Management Unit (CFMU). The CFMU schedules flights as such that no uncontrollably large flows of flights occur in an ATM sector. The CFMU does so by, amongst others, ground-holding. [1] If a flight is put into a ground-holding the flight's departure will be delayed until a suitable departure slot comes available that ensures the flight not causing congestion in other sectors. This process is based on flight plans that pilots have to issue prior to departure.

The other part, most fundamental, is tactical control as is in the current Air Traffic Management (ATM) system done by the Air Traffic Controller (ATCo): The ATCo ensures the real-time separation of flights in his sector by issuing heading and speed changes. At the moment this process can not be done in advance, i.e. prior to the flight's departure, as the presence of disturbances in an aircraft's trajectory make it's behaviour non-deterministic.

2.2.2 Required Time of Arrival

The fact that currently flights are too non-deterministic for planning to be done on forehand can be overcome in the future if more use is made of the so-called Required Time of Arrival (RTA) functionality as installed on most modern Flight Management Systems (FMS). [6] This RTA functionality aims to let aircraft overfly waypoints at a pre-determined time. This pre-determined time is issued by the ATCo (or potentially in the future by an automated system) as a Controlled Time of Arrival (CTA). This CTA only becomes an RTA once it is programmed into the FMS.

An FMS with an RTA functionality is operating an RTA algorithm that tracks the RTA. This is done by comparing the ETA and the RTA. This ETA is calculated based on the flight plan, and the planned Mach number as programmed in the FMS. If the difference between the ETA and RTA is larger than a tolerance, typically 6 or 30 seconds, a speed correction is made. The earlier speed changes are made, the more effective they are. Conversely, the same speed correction will have a larger impact if it is done at the beginning of the flight than if it is done at the end of the flight. This results in the so-called RTA 'Control Funnel' of Figure 2.1 as coined by Wickman et al. in [7].

If one wishes to base aircraft operations on RTAs it is of crucial importance that these RTAs are achieved with a reasonable tolerance. To this end field trials have been done

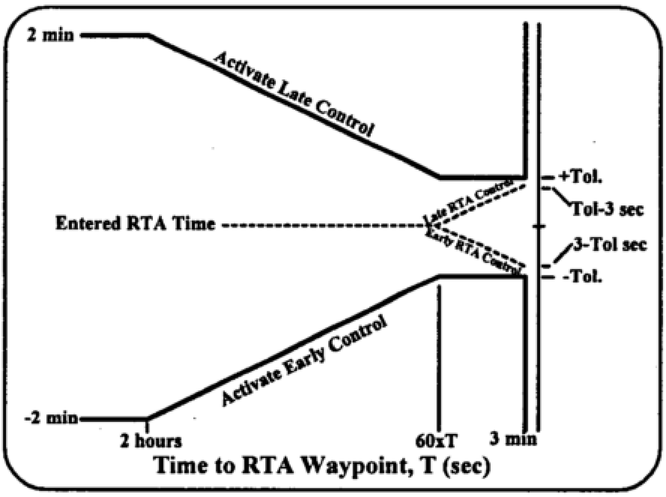


Figure 2.1: RTA control funnel, adapted from [7]

by Wichman et al. as described in [7]. For these trials 33 flights of SAS in Sweden were analysed. It appeared that from departure to the top of the STAR (Standard Terminal Arrival Route[2]) the maximum time off-set was 7 seconds. Some flights were excluded from this statistic as they were vectored off their flight plan by Air Traffic Control (ATC). It was also noted by Wichman et al. that if the wind predictions, as entered in to the FMS, are accurate, the ETA in the FMS will be very accurate, resulting in good performance of the RTA algorithm.
Flight trials at Seattle Tacoma Intl Airport as performed by Balakrishna et al. and reported in [8] found similar results. These flight trials also included pilot interaction with the RTA algorithm and were done over a larger flight distance. In conclusion it can be said that aircraft can reliably enter a STAR at a controlled time of arrival, with a relatively small error.

2.2.3 Arrival Scheduling Management

Having established a reliable way in which it can be assured that aircraft enter the STAR at a specific arrival time, it is time to move towards the other aspect of this literature study, namely the way in which aircraft are scheduled for arrival. Arrival scheduling is more a prioritization exercise than a planning exercise as currently time information is not specific enough to be used by time-scheduling algorithms in the latter stages of the flight. As a consequence, ATCos use a system known as First-Come, First-Serve (FCSF) to prioritize flights. [9] FCFS means that an ATCo lets that aircraft land first that is closest to the runway, i.e. has the least distance to fly. This is implicitly assuming that all aircraft fly the same speed and are subject to no (or the same) disturbances along the latter stages of the flight.

[2]As the ends and means of a STAR are not directly relevant for this project no further information is included on the working of a STAR.

Equitability

A direct consequence arising from the observation that arrival management is essentially arrival prioritization is the need for fairness when handling competing requests. Even though it could seem common sense for an ATCo to prioritize aircraft with larger fuel burn rates, it is important that he does not do so. Such a practise would harm short-haul carriers while giving an advantage to long-range flights. It is hence important that any scheme that is designed to replace or amend FCFS is fair to all users of the airspace.

The need for fairness, or equitability as it is more commonly called, of an arrival management scheme can in different ways be incorporated. On the one hand this can be done implicitly. This means that a scheme is not specifically designed for fairness, but are equitable by nature. FCFS is such a system. On the other hand a schedule that is in itself prioritizing a specific type of flights or aircraft can be made explicitly equitable by introducing an additional parameter in it. One such scheme is Equity-Based Ration-By-Distance (E-RBD) as proposed by Ball et al. in [10].

Aircraft Landing Problem

To formalize the problem of scheduling flights that are inbound for arrival Beasley et al. have formulated the Aircraft Landing Problem (ALP) in [11]. They state that the problem is such that for each of the aircraft in a set a landing time has to be determined, so that each of the aircraft land within a predetermined time window. Also, they take into account separation criteria. They propose the use of a single cost function that assumes a linear relationship between incurred costs and amount of deviation from the scheduled arrival time, and hence can be seen as a particular version of the absolute deviation objective function as proposed by Brucker in [12].
The problem Beasley et al. state can be seen as a static optimization problem, as at the onset of the optimization effort all information about all aircraft is known, i.e. the amount of aircraft is fixed and disturbances are known. A more realistic problem to solve would be the dynamic case as proposed by Mesgarpour et al. in [13]. In this case aircraft enter the analysis domain on a continuous basis.

Fuel Consumption

The objective function Beasley et al. propose assumes a linear dependency between earliness and tardiness. Even though this seems to be appropriate for the ends they use it, it is not taking into account the non-linearity of fuel burn increase as flight speed is increased. A more detailed cost function can be obtained by making use of the results of Delgado et al. in [14]. The same researchers look for ways to cover departure delays as a function of cost index in [15]. They conclude that a small increase in flying speed over a long time is more fuel efficient than a large speed increase over a short time, a notion that is supported by Tielrooij et al. in [2].

Scheduling Managment for RTA-Capable Aircraft

Trajectory Based Operations (TBO) enables continuous control of the 4^{th} dimension, time. In controlling this fourth dimension, the use of the RTA functionality as described in subsection 2.2.2 may prove to be vital. This was also noticed by Haraldsdottir et al. in [16] where they analyse the concept of an arrival manager using RTAs. In this paper they describe an arrival manager that issues CTAs, and an FMS that has the authority to make speed adjustments independently of pilot or ATCo intervention to assure the aircraft overflies an Initial Approach Fix (IAF), the top of the STAR, at a specific time. From tests on Boeing's Trajectory Analysis and Modeling Environment (TAME) it appeared that their concept can realise a significant decrease in fuel burn, while not endangering flight safety, even in several extreme cases.

Probabilistic Arrival Planning Making use of Dynamic Arrival Windows

In an MSc thesis by Mitici ([4]) a new concept was introduced to schedule aircraft for a single runway. Instead of the currently available RTA environment where one RTA (or CTA) can be used, a new concept is envisaged that allows the usage of an RTA window. This RTA window has an early RTA, that assumes the aircraft flies at its maximum cruise speed and a late RTA, that assumes the aircraft flies at its minimum speed. Even though this approach was more from an operations research point of view, it still provides a valuable concept that is worth exploring further.

Based on a relatively simple model there appeared to be a significant improvement in terms of fuel efficiency. This model did not take into account detailed aircraft dynamics, and determined costs based on a linear, absolute deviation basis, similar to the one in [11]. Using a more detailed cost function that is based on more detailed aircraft dynamics can provide a better view on the possible gains that are to be expected from this method.

Even though the use of dynamic arrival windows for arrival planning is relatively new, the concept of target windows is not. For example, in [17] Han et al. describe a concept to quantify and visualize uncertainties in the adherence to spatial (trajectory) and temporal (CTA) constraints. Also, they propose a way in which such windows should be constructed.

Another paper that addresses dynamic windows in an ATM context is [18] by Margellos et al. Even though this paper is more about spatial variability and has a focus on conflicht avoidance, their methodology of assessing influences of sizes of such windows through Monte Carlo simulations could be extended into the time domain for sequencing.

2.3 Results and Analysis

Given the current strong distinction that is being made between the two types of air traffic control, being strategic control and tactical control as described in subsection 2.2.1, improvements may be possible by integrating the long-term view and the short-term conflict avoidance. To this end it is important to have a more precise view of the times at which aircraft enter a STAR. One such way would be to track aircraft precisely and anticipate when they do so, without making changes to the way in which aircraft fly. This would result in ETAs at the top of the STAR to fluctuate as a function of wind disturbances and ATCo heading and speed instructions. As it will expectedly prove to be difficult to build a reliable metric around this constantly fluctuating ETA it is necessary that aircraft move towards an RTA-centred flight operation, as is forecast by Trajectory Based Operations (TBO). Having omnipresent RTA capabilities in aircraft, as described in subsection 2.2.2, would pave the way for arrival managers to schedule aircraft based on their arrival time. Given the high accuracy of readily available RTA algorithms (as long as wind forecasts are accurate) very small tolerances can become possible.

Several attempts have been made to incorporate RTAs into the scheduling phase, but most of them have been aimed at maximizing aerodrome capacity, and only several at minimizing costs for airlines. The cases that were aiming to minimize costs for airlines made use of a very simple model for flight costs. It was assumed that costs of deviations from a scheduled arrival time are linearly proportional to the amount of time between the actual and scheduled time of arrival, and that they are symmetric (i.e. 60 minutes early has the same cost impact as being 60 minutes late). It can be worthwhile to make use of a more detailed cost function that takes into account the complex fuel dynamics of an aircraft.

In addition to the more detailed cost function is appears to be worthwhile to also investigate the use of dynamically varied arrival windows as discussed in section 2.2.3. For the concept as proposed by Mitici in [4] a more detailed fuel model is necessary before the results can be quantified, as also this paper assumes symmetric, linear costs based on deviations from a scheduled time of arrival. If Mitici's work is used as the basis for analysis, but with a more detailed cost model, two steps can be taken, by extending both the work of Mitici and the paper of Beasley. For the eventual result being viable for use in the air management spectrum it is important that the system ensures equitability for all flights and aircraft.

2.4 Discussion and Conclusions

In this literature review a brief overview has been given of the current state of research in the field of arrival managment, with a particular focus on the use of RTAs for scheduling. Concepts like equitability, fuel consumption and RTA passed review. It appeared that even though there is a vast amount of research in the field of arrival management, there is only a limited proportion of it dedicated to the use of RTAs in this context, and an even more limited portion to the decrease of costs for airlines.

It came apparent that currently available research typically makes use of a very simple cost function to base analyses and optimisations on. This is a valuable entry point to continue from in the work of Mitici and the paper of Beasley, as both lack in this area. It can hence be recommended that further research is done. From this research it should come clear whether the mentioned concepts indeed provide the increases in efficiency that were found thus far. If this appears to be the case, it could provide a solid basis for further research and implementation.

Chapter 3

Research Plan

3.1 Introduction

Over recent years, especially with the advent of aviation modernisation efforts like SESAR[1] in Europe and NextGEN in Northern America, several old customs are being reviewed. One such custom is the way in which Air Traffic Controllers do their job. Currently, they use a method known as First-Come, First-Serve for scheduling flights for arrival. This is not necessarily the most efficient in terms of fuel consumption.

To address the shortcomings of the current methods several attempts are under way to aide the Air Traffic Controllers in the scheduling process. This is generally done through the use of Arrival Schedulers that make an attempt to give controllers a better insight in how his aircraft will be sequenced. These schedulers currently work primarily based on deterministic variables like expected time of arrival, and do not take into account deviations in actual weather and forecasts.

In order to make the behaviour of aircraft more predictable it can be worthwhile to look at the Required Time of Arrival function in the Flight Management System. This system controls the speed an aircraft flies at to have it overfly specific waypoints at predetermined times.

This article will be the proposal for a project that makes use of dynamic windows of these Required Times of Arrival to pave the way for more efficient flight operations by giving more freedom in terms of desired speed to the pilot (and through him to the airline) while mitigating the need for holding patterns near the destination airport.

In section 3.2 the objectives of the research and the research questions will be formulated. Section 3.3 will provide the theoretical basis of the project and will formulate the hypothesis. Also, it will divide the to-be undertaken work into work packages with clearly defined goals. In section 3.4 the expected format of the results of the project will be discussed. Also, a brief elaboration is made on the need for verification and validation, as well as the way in which this will be done. Finally, in section 3.5 conclusions will be drawn from the matter presented in this project proposal.

[1]Single European Sky ATM Research

3.2 Research question, aims and objectives

The aim of the research is twofold: One part was focussing on the design of a scheduler that makes use of dynamically varying required time of arrival windows while putting a central focus on cost reduction due to unnecessary fuel usage. The other was about the construction of these dynamic RTA windows. The idea is to reduce the system-wide costs of fuel by smartly issuing CTA windows to aircraft that are still in the cruise phase and a considerable distance away from their top of descent. Due to the nature of the airline industry, particularly for network carriers, it is important to actively address the mitigation of delays, too, in order to reduce the costs.

Finally, the developed method needs to be assessed, to test the robustness of it, and to quantify the gains that can be achieved by the introduction of this method. This calls for the simulation of a realistic environment in which both currently prevailing methods and the newly developed method can be put to the test.

The main objective is to assess the possibility and efficiency of making use of dynamic arrival windows to improve arrival management. First it will have to be defined how use is going to be made of such windows. It should be kept in mind that the eventual objective of this is to reduce the system-wide fuel usage while keeping system-wide delays manageable. The point of departure will be the model Mitici proposed in [4].

The main research question has been defined as being *"How can the efficiency, measured in economic terms as resultant of unnecessary delays and fuel usage, of flights be improved by dynamically controlling the CTA time windows of arriving flights until the initial approach fix, and what is the effect on efficiency?"*. Given this main question, a set of subquestions, with accompanying subsubquestions, has been compiled.

1. **What influence do delays and fuel usage have on the cost of a flight, and how can it be quantified?**
2. **How should a CTA time window be constructed and dynamically altered in time?**
3. **What would be an appropriate way to assess the efficiency of different scheduling methods, and what parameters should the methods optimize for?**
    3.1. What would be an appropriate way to define a cost function?
4. **How can the defined cost function be optimized by dynamically controlling CTA time windows?**
    4.1. How can this be formalized in a scheduling algorithm?
5. **How can scheduling algorithms be assessed?**
6. **What is the impact on the cost of the newly developed method in comparison to the currently implemented FCFS arrival management methodology?**

6.1. What is the impact w.r.t. delays?

6.2. What is the impact on fuel usage?

6.3. What is the impact on the defined cost function?

7. **Do these results agree with previously done similar research?**

8. **What are the implications of the performed research for (future) research and implementations?**

9. **What recommendations can be done for follow-up research?**

3.3 Methodology

The first work package will propose a more detailed cost function that makes use of aircraft and fuel dynamics. Also, in work package 1, the methodology to construct the dynamic time windows will be constructed.
The second work needs the results of work package 1 as the scheduler will optimize for the detailed cost function that is derived in question 1, by making use of the required time of arrival windows as derived in question 2.
The third work package then puts together the results of the newly developed methodology, and two already existing approaches, namely First-Come, First-Served and Ration-by-Distance, to assess the gain (or loss) in costs.
Finally, the fourth work package discusses the impact of the project, and its implications for future research and developments.

3.4 Results, Outcome and Relevance

The data that are coming from the simulations will be of a dual format: On one side there will be the cost data of the flights, namely the cost directly proportional to the hours flown, and the cost due to fuel usage. On the other side there will be the data giving the arrival times of each of the flights in the simulation, compared with the planned times of arrival. These data will be put into an aggregate cost that combines the costs of being late with the other costs to assess the performance of the newly developed methodology. This will be used to determine the suitability of the newly developed methodology to reduce the costs of flight operations for airlines.

3.5 Conclusions

There is currently a strong distinction between tactical and strategic control. This project aims to integrate these two, while giving more freedom to the pilot and the airline. This should have a cost-reducing impact on the overall system, and hence should increase the overall efficiency of the aviation industry. In addition, if the to-be designed concept seems viable, it can be a strong incentive for the aviation community to increase the speed at which Trajectory Based Operations, in particular RTA-ability is implemented, which could prove to be an important step along the path of making aviation future-proof.

Nevertheless, the ambition that is in this project should be clear from the fact that it aims to combine dynamic RTA-windows and a non-linear, non-symmetric optimization function. Thus far there has been no research that combined normal, singular RTA's with a non-linear, non-symmetric cost function, let alone with (dynamic) RTA-windows. This means that there is a moderately large risk of running into setbacks as the project aims to explore uncharted territories in two directions.

Chapter 4

Quantification of Costs

When assessing the cost of flights from a monetary perspective - one can also assess flights from an environmental perspective amongst others - it is important to realize how these costs are attained. As we are interested in this thesis in the costs for an airline that is operating the flights we need to establish what costs are influenced by changing the CTA, and how to quantify these changes.

First of all it is important to establish what costs airlines incur. In the airline case a suitable way to differentiate would be between costs that are independent of the amount of flight hours and those that are. This is more appropriate as most airlines operate on a fixed schedule, seemingly independent of the amount of seats sold.

Costs of interest for this research are costs like fuel, maintenance and crew salaries. In corporate finance these costs are referred to as variable costs, as they increase with increases in sales. As the research that is reported in this thesis is solely concerned with costs of time and fuel the fixed costs (in corporate finance jargon) will not be included any further.

4.1 Variable Costs

In the following we will define variable costs as being costs that are directly impacted by the amount of hours of flight operations. Below a summary will follow of variable costs, their origins, and their implications.

- **Crew Costs:** A strong distinction is to be made between flight-deck crew, i.e. the pilots, and the cabin crew, i.e. the flight attendants. Even though there are different levels of salaries for pilots - a captain will earn significantly more than a first officer - these costs do not vary on an hourly basis: Once it is determined what the total hourly crew cost is for a specific type of aircraft it can be multiplied by the amount of hours the aircraft is operated.

- **Maintenance Costs:** Another important variable cost is the maintenance cost. Even though this would seem as a fixed cost, it is really variable as aircraft maintenance intervals are denominated in terms of hours flown and numbers of flight cycles. Hereof the amount of flight hours is typically dominant, and hence the maintenance costs can be seen as directly proportional to the amount of hours the aircraft is operated.

- **Fuel Costs:** Fuel costs are the costs that are incurred by the burn-off of fuel in the aircraft's engines. These costs will increase if more hours are flown and if the aircraft flies at a higher velocity.

From these variable costs another division can be made: those variable, or hourly, costs that change with changes in flight speed, and those that don't. Those that don't are crew cost and maintenance cost. This has to be understood correctly: if velocity increases these costs will decrease as less time is spent flying, but their hourly costs won't. The contrary is true for fuel usage, as this cost increases per unit of time with increases in speed.

4.2 Fuel Costs

Having determined what the fuel-independent variable costs are, only the fuel-dependent variable costs remain to be determined. To do so it is important to understand how aircraft fly, and what dominates fuel usage. In Figure 4.1 the forces that are acting on an aircraft in steady horizontal flight are shown. In the following it is assumed that aircraft fly in a steady, horizontal flight over the sections that are to be considered.

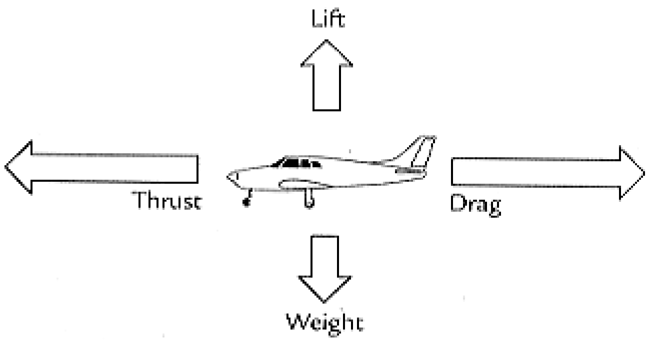


Figure 4.1: Forces acting on an aircraft in steady, horizontal flight, adapted from [24].

In steady, horizontal flight there is no altitude gain and no acceleration. This means that the forces in the horizontal and vertical directions (when looking at the aircraft from one side like in Figure 4.1) sum up to zero. In the horizontal direction this means that $thrust = drag$, and in the vertical direction that $lift = weight$.

The amount of fuel that is being burnt is dependent on the amount of thrust that the engines generate. Then, using the definition of Thrust Specific Fuel Consumption (TSFC), the fuel flow per time unit can be found to be $\dot{m}_f = c_{TSFC} * T$.

Using the assumption of steady, horizontal flight we know that $T = D$, so we need to find out what the Drag is. From basic aerodynamics this is known to be $D = \frac{1}{2}\rho V^2 C_D S$, with ρ being the density of air, V the flight speed, C_D the aerodynamic drag coefficient and S the surface area of the wings. For the Boeing 777-300ER the wing area is known to be $S = 427.8\ m^2$ [25]. The air density ρ can be found by making use of the International Standard Atmosphere [26]. The flight velocity is one of the variables that is subject to change in this analysis.

The remaining quantity is the aerodynamic drag coefficient C_D. This quantity can be approximated by taking $C_D = C_{D_0} + KC_L^2$, where the first quantity on the right hand side is the parasite drag and the second quantity the lift-induced drag.

The parasite drag varies with changes in the Mach number: as the Mach number increases, the parasite drag increases due to transient effects associated with the approach of the speed of sound. Using values for the evolution of C_{D_0} from [27] a fourth-power regression was used to approximate the behaviour of the parasite drag between Mach numbers 0.75 and 0.86. The polynomial that describes this relationship was found to be $C_{D_0} = 14.116 - 73.7623 * M + 144.7623M^2 - 126.267M^3 + 41.3333M^4$. It can be seen that the parasite drag is fairly constant up until approx. $M = 0.80$. When flying at a higher Mach number the value increases dramatically.

The K in the lift-induced part is a constant that has a value of $K = 0.0431$ for the B773ER. The lift coefficient C_L can be found with $\frac{L}{\frac{1}{2}\rho VS}$. Using again the assumption of steady, horizontal flight we find that $L = W$.

Using the above C_D can be determined, from it the drag D, and consequently the thrust T. This quantity then leads to the fuel flow in kg per second when taking $\dot{m}_f = c_{TSFC} * T$. For the General Electric GE90-115B1 engines of the B773ER the TSFC is known to be $c_{TSFC} = 0.00000783\ \frac{kg}{Ns}$.

Once the fuel flow per second is known the determination of the amount of fuel that is used over a set flight distance is a trivial exercise of multiplying the fuel flow per second by the flight time.

Once the amount of fuel used is known we can find the cost by multiplying the fuel mass by the cost per liter. It is assumed that jet fuel has a density of 1 kg/L. The price of jet fuel varies with changes in crude oil prices. For this analysis a moderate peak in oil prices will be used that resulted in a price of 1.92 US$ per gallon of JP-A1 jet fuel.

4.3 Total Costs

Having established the individual cost components, the total variable cost of a flight can be determined by summing all individual components. In doing so it is required that a model for the evolution of air density ρ and speed of sound a with altitude. An appropriate model would be the International Standard Atmosphere (ISA) as is described in [28]. In the model for this research use has been made of the stock ISA function in Matlab R2016a *atmosisa*. This function has as outputs the atmospheric properties from inputting the flight altitude.

In Figure 4.2 a plot is given of the costs for an aircraft as function of its flight velocity.

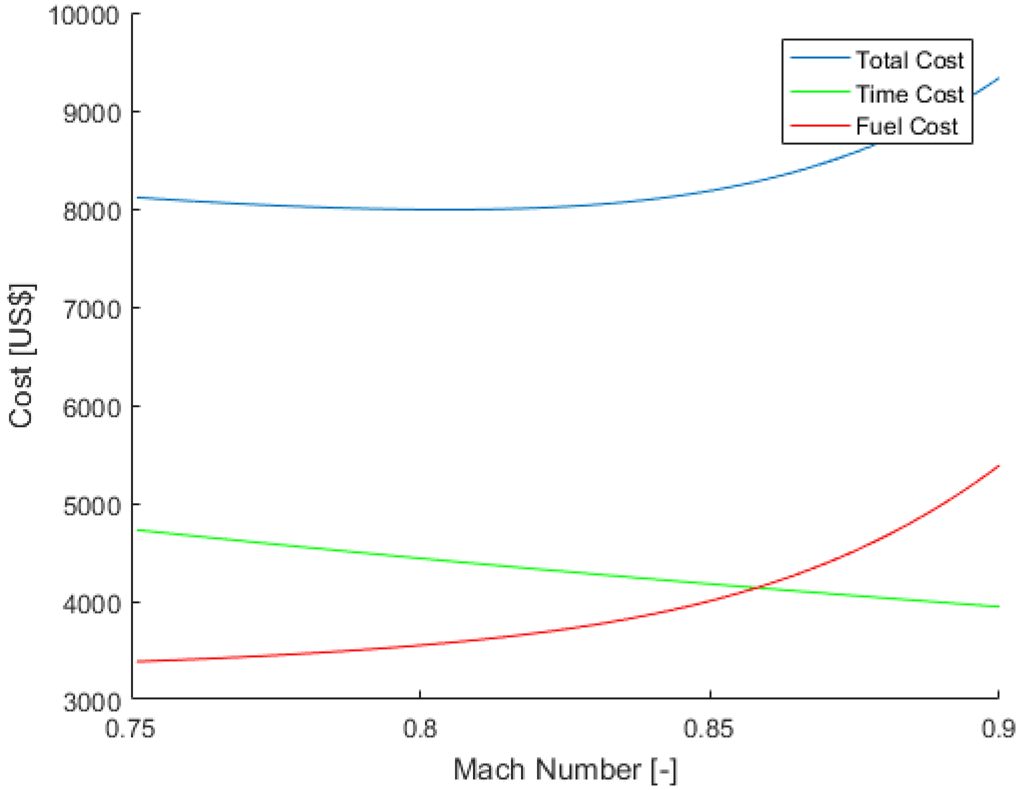


Figure 4.2: Modelled total cost and individual cost components of a Boeing 777-300ER as a function of for flying a section of 950km at FL350.

To relate the costs of fuel to the costs of time the notion of Cost Index (CI) has been introduced. The CI is defined as $CI = \frac{C_T}{C_F}$ [29] where C_T is the unit cost of time (e.g. \$/min) and C_F is the unit cost of fuel (e.g. \$/kg). Making use of this definition a cost function for the total costs of a flight can be derived (see Equation 4.1).

$$CF = Fuel + Time * CI \tag{4.1}$$

In Equation 4.1 the CI is used to write the time in terms of kg of fuel. Strictly spoken, the final unit of CF can be read as 'kg of fuel', but it would be more correct to refer to CF as being in terms of 'kg of fuel and CI-converted time'. The advantage of making use of the CI-expression for the costs of a flight is that different cost factors can be used. This is more realistic as airlines have, due to differing priorities and business models, differing costs for hourly costs and fuel-related costs.

The in this chapter developed cost calculation methodology will be used as basis for a cost function in chapter 6.

Chapter 5

Wind Modelling

An important factor of influence on ETA, and hence also RTA is the wind speed. In a world where wind would not be present a single aircraft could fly at such a speed that it arrives at its destination at exactly the allocated RTA without changing its speed. It is important to mention that it is a single aircraft as the presence of other aircraft could lead to disturbances for collision avoidance reasons. In the real world, however, there are constantly winds present that are of a stochastic nature. This chapter will look into the way aircraft perceive winds, and on how these can be modelled to let aircraft in a simulation be subject to realistic wind effects.

5.1 Real Wind State and Observed Wind State

In the situation when winds are included in an analysis, it is important to understand how these influence flights. For the discussion that follows a 1D environment will be considered that can be seen as an in-trail view of the analysis space. Stochastic winds can be considered as information processes as at different times (and also in different locations) other knowledge is available about winds.

First it is important to make an explicit distinction between the 'real' wind state and the 'observed' wind state. The real wind state is the actual, current state of winds in the analysis domain, whereas the observed wind state is the observation of the real wind state by an observer. This observer is not directly someone who, or some institute that, observes wind, but rather a physical place where information is gathered or compiled regarding the real wind state. One current example hereof is the Rapid Refresh (RAP), the successor of the Rapid Update Cycle (RUC). Both the RAP and RUC were developed and administered by the National Oceanic & Atmospheric Administration (NOAA) of the United States of America.

The information that is used as input for this compilation is obtained from weather stations across the analysis domain that measure the real wind at that location. As this measurement is essentially an observation of the real wind, there will be a measurement error present that will be propagated into the compiled observation of the wind state. Moreover, the measurements that are used in the observation will not be fully real time, as some time is required to transmit the wind data to the observation station and to do the calculations for the compilation. Also, there may be differences between different observation stations as they may be using differing calculation methods or different weather stations. These different observation stations can be different stations on the ground (for example, they are located in different countries), or could be the ground station of the ATCo and the FMS of an aircraft.

In summary, it can be said that the wind state that is used by airspace users and controllers is an observation of the real wind state, with measurement and calculation errors in it. The observation is based on historic data and therefore outdated. Also, different observations of the same real wind state may be present in different observation locations. As aircraft are affected by the real wind state observations aim to approach the real wind state as closely as possible.

5.2 Wind Forecasts

Now that a distinction has been made between the real and observed wind states, that are purely focussed at assessing the current state of the wind, it is now time to introduce a time component. This is necessary as flights take some time to complete and the weather state at the onset of the flight will be different from the weather at the end of the flight and during the flight.

At a certain time it is uncertain how winds will be like at times after that time. It is however possible to make forecasts hereof that are accurate to a certain extent [30] [31]. These forecasts are typically produced by meteorological services. One current example hereof is the Rapid Refresh (RAP), the successor of the Rapid Update Cycle (RUC) that was used as the basis for the weather model in [32]. Both the RAP and RUC were developed and administered by the National Oceanic & Atmospheric Administration (NOAA) of the United States of America [33]. The NOAA RAP is run every hour to produce an 18-hour forecast.

If it is assumed that aircraft FMSs are loaded with the most recent NOAA RAP at the moment the flight departs. This means that in the worst case the wind forecast in an FMS is 59 minutes old at departure. If, however, this forecast is not updated during the flight, the forecast becomes more outdated as the flight progresses. Technically it is possible to uplink weather forecasts to aircraft, but this is typically only done at several-hour intervals, which entails that for the majority of the flight old wind data is used.

5.3 Errors in Wind Forecasts

As for any weather prediction, also wind speed forecasts have an uncertainty component. For this research it is of primary interest to investigate the impact of deviations of actual wind speeds w.r.t. their forecasts. This is because the uncertainty of wind speeds disrupts the predictability of ETAs and other time-planning in aviation. This section will look into the nature of wind speed errors and looks for a way to model them.

Wind speed errors result from deviations between expectations of wind models, and what the real world weather does. Typically wind forecasting systems like RAP an RUC provide so-called 'ensembles' of expected winds. Such an ensemble is the probability distribution of the wind (both magnitude and direction) at a certain location and altitude, as derived from the wind model. The average of the ensemble is used as the prediction. The spread of the ensemble is a handle for the uncertainty of the prediction.

Robasky et al. have studied the errors of RAP and RUC predictions in an ATM-planning context ([34]). Even though the performed study focusses at near-surface winds, the analysis of the so-called Terminal Radar Approach Control (TRACON) entry-box is interesting as this specifies the entry of the STAR, which is between approximately 5000 and 7000 ft. Even though this will not be a perfect proxy for winds at FL350 it does bear some useful insights. One of the interesting findings for the TRACON entry-box wind is the probability distribution of wind errors in Figure 5.1.

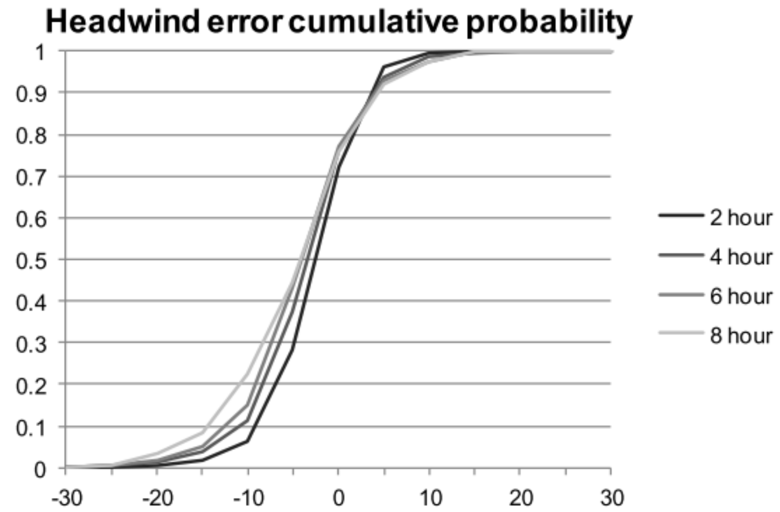


Figure 5.1: CDF of Wind Speed Error for the TRACON, adapted from [34]. Magnitude of wind speeds is in kts.

There seems to be a strong tendency for the error to be close to 0, which is obviously, a good thing. The error increases with increasing forecasting horizon. The error also seems to behave like a normal distribution, albeit with a skew towards underestimation.

Simulating Wind Forecast Errors

In order to take into account the uncertainty of wind forecasts it is necessary to develop a methodology that allows the forecast error to be simulated. Given the findings in Figure 5.1 it has been decided to assume a normal distribution for the wind error.

The wind error generator will generate errors at fixed time intervals, so it is necessary that the wind error at time t is a function of the error at time $t-1$. To bound the simulated forecasting error it has been decided to cap the error at +50 and -50 km/hr. To ensure that the error has a tendency to be close to 0, a mean-reversion to 0 is included by forcing a movement in the value towards 0. How fast this move towards 0 is is determined by the setting of the mean-reversion speed parameter γ. The resulting function for the generator is Equation 5.1.

$$\begin{aligned} \xi &= N(W_{t-1}, \sigma) \\ W_t &= \xi - \xi * \gamma \end{aligned} \tag{5.1}$$

Based on Figure 5.1 the setting parameters in Table 5.1 have been chosen. As basis the assumption has been used that the generator is run every 5 minutes. In addition, to exclude the possibility of having extreme values for the wind speed it has been decided to put hard limits to the maximum an minimum wind speeds, W_{UL} and W_{LL}.

Table 5.1: Setting parameters for the Wind Forecasting Error generator

Parameter	Value
σ	3
γ	0.020
W_{UL}	50
W_{LL}	-50

Using these settings 1000 runs of 120 consecutive error generations have been done. These numbers represent a thousand runs of each 10 hours with the error being generated every 5 minutes. The resulting empirical CDF can be found in Figure 5.2.

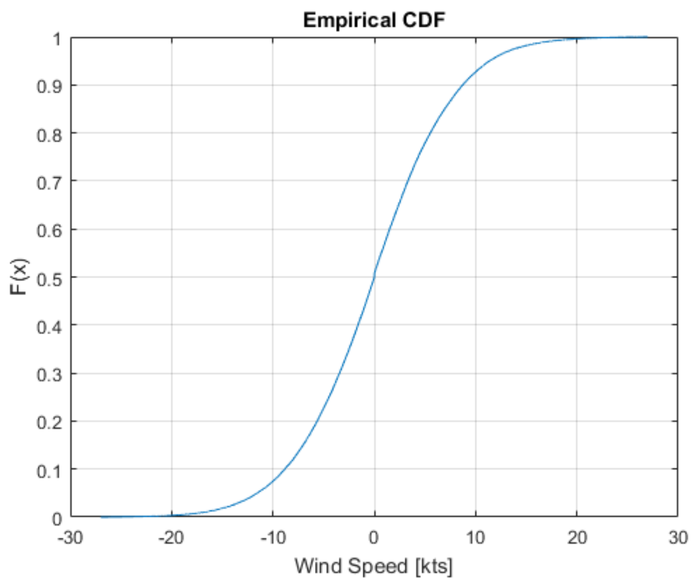


Figure 5.2: CDF of 1000 runs of 120 consecutive error generations.

It can be seen that the found CDF from the simulations is similar to that from the research by Robasky et al. ([34]). The most striking difference is the absence of a skew in the simulated values. This is the reason because no skew was taken into account in the generation of the errors. This is not expected to have an impact on the final conclusion from this research as a new scheduling algorithm will be benchmarked against other scheduling methodologies in the same testing conditions. This means that a tendency for wind forecasters to underestimate wind will both not be considered in the test and the benchmark simulations. This leads to the retention of validity of the results in view of real-world implementation.

Additionally the effect on the general shape of the upper and lower limits to wind speed, W_{UL} and W_{LL} has been checked. To this end the results of Figure 5.2 have been compared to a generation from the same wind algorithm, but without these limits. The resulting emperical QQ-plot can be found in Figure 5.3.

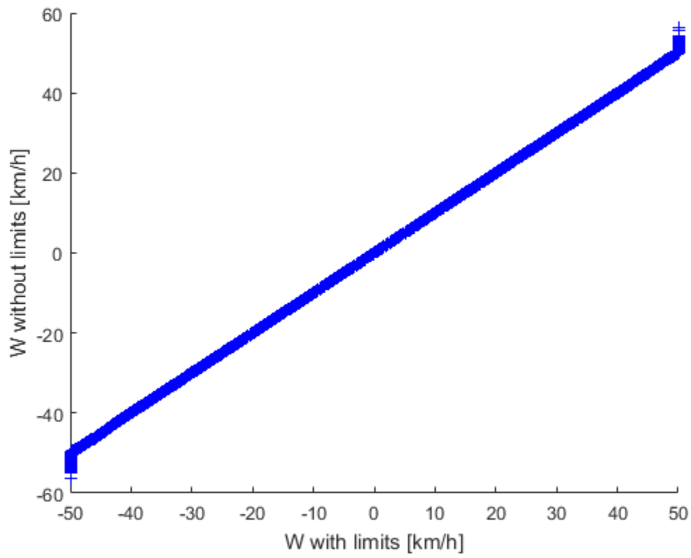


Figure 5.3: CDF of 1000 runs of 120 consecutive error generations.

It can be seen in Figure 5.3 that there are only very few deviations over the full run at the edges. This results in a slightly elevated probability of having values for the wind prediction error at the limiting values.

Chapter 6

Model

To assess different scheduling techniques it is important to have a method that is able to do so reliably. Given the nature of the research it is possible to identify two separate requirements of the assessment method: Firstly, it is important to assess the different scheduling methods in a representation of the reality wherein they will be applied, to gather different metrics from the aircraft for each of the methods. Secondly, the results from the different tests need to be assessed in terms of monetary costs for the aircraft. Use will be made of the discussion of chapter 5 on wind modelling.

The model that is used to assess the behaviour and performance of each of the scheduling techniques will be discussed conceptually in this chapter. Section 6.1 will discuss the way in which the techniques are assessed. In section 6.3 a cost function will be derived that will be used to assess the scheduling methodologies. An overview of the model can be found in section 6.4.

6.1 Assessment of Scheduling Techniques

To assess the different scheduling techniques it has been decided to design a simulation, similar to the Boeing Trajectory Analysis and Modelling Environment (Boeing TAME), as described and used by Haraldsdottir et al. in [16]. The Boeing TAME makes use of a 3D representation of an airspace and then simulates the flights of aircraft through this airspace, and lets the user test multiple aspects, one of which is the performance scheduling techniques. For this research use will be made of a 1D-simulation in which only the radial distance to a target (Initial Approach Fix), fuel usage and time consumption play a role.

Assumptions

In the following part a summary of the made assumptions and their implications for the results will follow.

- **Only the cruise phase is included in the analysis**
  as hardly any control can be exerted over the ETA during the climb, descent and landing. This is confirmed by both Wichman et al. and Bronsvoort et al. in [7]

and [35], respectively. As no control can be exerted, the exclusion of these parts will have no impact on the findings of the research.

- **Only one flight altitude (flight level) is considered.**
  Even though the altitude is considered in the calculation for the fuel cost, it is not taken into account during the cruise phase of the flight. As the research does not bother about cruise-phase separation this does not need to be considered.

- **Only one type of aircraft (Boeing 777) is considered in the analysis.**
  This is done for two reasons: Firstly, it simplifies the research as all aircraft have the same dynamics; Secondly, this research aims to identify the potential for a new method. If a new method is not more efficient when all aircraft have equal properties, i.e. all aircraft react identically, it won't have a positive impact for differing aircraft types. This means, conversely, that if a new method has a positive impact from a single aircraft-type case, additional research is required to confirm the positive impact in a multiple aircraft-type case.

- **Simulation time is discretized**
  so that the simulated aircraft can be evaluated in series. If time were continuous, all aircraft would have to be considered simultaneously, which would have complicated the simulation significantly. As a very small time step (1 second) is used for the simulation a continuous model is approached, and there is no impact for the outcome of the simulation. The simulation only stops when all aircraft have landed. It is therefore impossible to say what the time horizon will be in advance.

- **Aircraft are generated uniformly across the (spatial) analysis domain.**
  This means that, if no queueing happens (i.e. all aircraft can land without holding) the arrival rate is on average constant. Use is made of a uniform distribution: $U(R_{min}, R_{max})$; The aircraft are not generated based on an already existing schedule.

- **It is assumed that the speed of sound is constant throughout the analysis domain**
  so that a constant g can be used for all aircraft at all times. Even though this is not true in reality it greatly reduces the complexity of the simulation.

6.2 Parameter Definition

In this section a list will be given of all used parameters and their meaning.

A $= \{a^1, ..., a^m\}$ is the set of m aircraft that are under consideration.

C is the runway capacity in ac/hr.

CF is the average total amount of fuel and cost index-converted delay per aircraft.

$\overline{CF}$ is the average of CF over all runs of the Monte Carlo simulator per aircraft.

CI_{max} is the maximum cost index until which CI's can be generated.

CI_t^i is the cost index of aircraft a^i at time t.

CTA_t^i is the Controlled Time of Arrival of aircraft a^i at time t.

D_{thr} is the window threshold density, i.e. the upper limit of density of preferred arrival times in a window.

$DPTA_t^i$ is the density of PTAs, i.e. the number of aircraft with their preferred arrival time in the window correspondent to aircraft i at time t.

ELT_t^i The earliest possible landing time for aircraft a^i at time t.

ETA_t^i is the Expected Time of Arrival (ETA) of aircraft a^i at time t.

F_t^i is the amount of fuel that aircraft a^i has used until time t in kg.

$f^i(V_t^i)$ is a function that calculates the fuel flow per second of aircraft a^i, based on its speed V_t^i at time t.

FB_t^{i-} The average required fuel burn in kg for aircraft a^i at time t to be accelerated w.r.t. PTA^i per minute time gain.

FB_t^{i+} The average required fuel burn in kg for aircraft a^i at time t to be delayed w.r.t. PTA^i per minute delay.

g_t^i is the speed of sound for aircraft a^i at time t.

H_t^i is the set of aircraft a^j that have their PTA_t^j in the time window that corresponds to aircraft a^i. $H_t^i \subseteq A$

K is the number of runs of the Monte Carlo simulation.

LLT_t^i The latest possible landing time for aircraft a^i at time t.

m The number of aircraft to be considered in the simulation.

$M_{cr,max}$ is the maximum cruise Mach-number. This is the Mach-number that corresponds to CI being maximum.

$M_{cr,min}$ is the minimum cruise Mach-number. This is the Mach-number that corresponds to $CI = 0$.

PTA_t^i The Preferred Time of Arrival of aircraft a^i at time t as calculated from the FMS given its position w.r.t. its schedule; It is that arrival time that minimizes the total cost. This value acts as the target.

$pta(r_t^i, W_t^i, CI^i)$ is the function that determines PTA_t^i, making use of r_t^i, W_t^i and CI^i.

r_t^i is the distance aircraft a^i has to fly until the Initial Approach Fix (IAF) at time t.

R_{max} is the maximum distance until which aircraft can be generated.

R_{min} is the minimum distance from which aircraft can be generated.

S^{ij} The minimum time separation between aircraft a^i and j, if aircraft i lands before aircraft j.

t is the time in s since the start of the analysis.

$U(l, r)$ denotes the Uniform number generator that draws uniformly between l and r.

V_t^i is the velocity of aircraft a^i at time t.

W_t^i is the difference between the actual wind speed and the forecasted wind speed (i.e. the wind speed error) that aircraft a^i encounters at time t. Wind speed is defined to be positive when it is a tailwind. The forecasted wind speed is defined as being 0 for all aircraft at all times.

$w_t^i(\alpha)$ is the probability distribution function of the future wind error along the path of aircraft a^i at time t. The setting parameter α gives the α^{th} percentile of the wind ensemble.

WL_t^i is the length in time units of the time window corresponding to aircraft a^i at time t

α^+ is the upper choosing parameter for the draw from the wind ensemble. The higher it is the higher the maximum tail wind that is considered will be. $100 \geq \alpha^+ \geq 50$

α^- is the lower choosing parameter for the draw from the wind ensemble. The lower it is the higher the maximum head wind that is considered will be. $0 \leq \alpha^{-} \leq 50$

ϵ_{TC} is the time control speed update threshold. The lower this parameter is, the more frequently the aircraft will update its speed.

τ_s is the time resolution of a possible scheduling algorithm.

τ_w is the time resolution of the wind update algorithm.

$|X|$ Denotes the cardinality of the set X.

6.3 Cost Function

Having established the individual contributors to costs for aircraft, now the cost function for the model of all aircraft is defined. This is the quantity that the eventual scheduling technique should aim to minimize. The simulation starts at time $t = 0$. All calculations for this cost function will take place at the end of a simulation, i.e. after all aircraft have landed at time $t = T$.

Let ETA^i_t be the Expected Time of Arrival of aircraft i at time t. ETA^i_T is equal to ATA^i, the Actual Time of Arrival of aircraft i. Only the airborne portion of the delay will be included in the calculation. This means ETA^i_0 can be seen as a scheduled arrival time as delays will be determined based on this quantity.

Let there be m aircraft in the analysis domain. Then, the cost function for a single aircraft i can be calculated as the sum of fuel cost and time cost:

$$CF^i = C^i_{Fuel} + C^i_{Time} \tag{6.1}$$

The costs will be calculated w.r.t. a cost benchmark for aircraft i. This cost benchmark is defined as being the total cost of aircraft i, if it arrived exactly in time, so $ETA^i_T = ETA^i_0$, and it flew at its intended speed.

Given an aircraft's cost index, defined as $CI^i = \frac{c^i_{Time}}{c^i_{Fuel}}$, where c^i_{Fuel} and c^i_{Time} denote the unit cost of fuel and time of aircraft i, respectively. If the cost benchmark is included, this yields the cost function of aircraft i, expressed in kilogrammes and kilogramme-equivalents:

$$CF^i = (F^i_{act} - F^i_{benchmark}) + Delay * CI^i \tag{6.2}$$

F^i_{act} is the actual total fuel usage. It can be determined by using the instantaneous fuel usage.

The instantaneous fuel usage, i.e. the fuel usage in kg per second can be calculated using the in section 4.2 derived function. This function is, if the type is fixed to a B773ER dependent on the weight of the aircraft and its flight speed. As the influence of weight on fuel usage is minimal w.r.t. changes in flight speed, the aircraft weight variable will be kept fixed. This means that in this research the function is purely dependent on the flight speed of aircraft i, V^i. This fuel function is referred to as $f(V)$. Bear in mind that V^i does not need to be constant over the entire flight.
The total amount of fuel that was used by aircraft i can then be found, after it has landed, as being:

$$F^i_{act} = \int_{Starttime}^{ETA^i_T} f(V^i)dt \tag{6.3}$$

Herein V^i is the velocity profile per time of aircraft i. It has to be noted that all aircraft start flying at the beginning of the simulation, albeit at different distances away from the target. The benchmark fuel cost can be found to be:

$$F^i_{benchmark} = \int_{Starttime}^{ETA^i_{Starttime}} f(V^i_{Starttime})dt \tag{6.4}$$

Where $V^i_{Starttime}$ denotes the planned velocity of aircraft i. As $V^i_{Starttime}$ is a constant, Equation 6.4 can be evaluated as being:

$$F^i_{benchmark} = \int_{Starttime}^{ETA^i_{Starttime}} f(V^i_{Starttime})dt = (ETA^i_{Starttime} - Starttime) * f(V^i_{Starttime}) \tag{6.5}$$

Having established the individual fuel-related quantities in Equation 6.1, now a closer look is taken at the delay component. As mentioned before, only delays that have been incurred during the flight will be considered. There is however a problem if the plain difference between the initial ETA and the ATA is taken. If an aircraft arrives earlier than $ETA^i_{Starttime}$, it is calculated as a benefit, however, in reality this is not such a benefit. It lies in the nature of the airline industry that arriving with a delay has a far greater cost than arriving early has as benefit. To overcome this the definition of delay is altered so that it only considers actual delay:

$$Delay = (ETA^i_T - ETA^i_{Starttime})^+ \tag{6.6}$$

Now, combining the found quantities into Equation 6.1 the cost function for 1 aircraft is found:

$$CF^i = \left(\int_{Starttime}^{ETA^i_T} f(V^i)dt - ETA^i_{Starttime} * f(V^i_{Starttime}) \right) + (ETA^i_T - ETA^i_{Starttime})^+ * CI^i \tag{6.7}$$

To then find the cost function for the combination of all considered aircraft, Equation 6.7 is then summed over all m aircraft and divided by m to find the Cost Function average per aircraft:

$$\begin{aligned} CF &= \frac{1}{m}\sum_{i=0}^{m} CF^i \\ &= \frac{1}{m}\sum_{i=0}^{m} \Bigg(\int_{Starttime}^{ETA^i_T} f(V^i)dt - ETA^i_{Starttime} * f(V^i_{Starttime}) \\ &+ (ETA^i_T - ETA^i_{Starttime})^+ * CI^i \Bigg) \end{aligned} \tag{6.8}$$

This quantity serves as the performance metric for the to be assessed scheduling methodologies. A lower CF indicates a better performance of one scheduling algorithm in comparison to another.

6.4 Testing Model Overview

Given the in section 6.3 developed cost function (Equation 6.8) this section will give an overview of the simulation model that will be used to assess the different scheduling techniques.

6.4.1 Simulation Algorithm

```
set t = 0
while ∃r^i > 0 do
    foreach a^i ∈ A do
        if r^i_t > 0 then
            r^i_t = r^i_{t−1} − δt ∗ (V^i_t + W^i_t)
            F^i_t = F^i_{t−1} + f^i(V^i_t) ∗ δt
            if Active cost control by aircraft is enabled then
                Claculate the optimal flight speed for a^i by executing algorithm
                 algorithm 4. if V_{PTA^i_{Starttime}} − V_{ETA^i_{Starttime}} > ϵ_{TC} then
                    Update V^i_t with the value from the PTA optimizer.
                end
            end
        else
            Do Nothing
        end
    end
    if r^i_t ≤ 0 & The time since an aircraft last landed is larger than the separation
     minimum then
        Fix t, r and F for aircaft i and exclude it from the simulation.
    end
    if t is divisible by τ_w then
        foreach a^i ∈ A do
            Update the wind speed error W^i_t by making use of the wind algorithm
             developed in chapter 5.
        end
    else
        W^i_t = W^i_{t−1}
    end
    if t is divisible by τ_s then
        Execute the scheduling algorithm (if applicable, e.g. if RBS is active).
    end
    t = t + δt
end
T = t (the end time)
CF = 1/m ∑_{i=0}^{m} CF^i
```

Algorithm 1: Simulation Model that assesses the performance of scheduling algorithms.

The algorithm can make use of the Preferred Time of Arrival (PTA) as calculated by an algorithm that is given in subsection 7.4.1 if the automatic speed update by aircraft is enabled. If it is enabled aircraft will autonomously update their flight speeds to the most cost-effective speeds given their CI and expected arrival time if the difference between the velocity corresponding to the preferred arrival time ($V_{PTA_t^i}$) and expected arrival time ($V_{ETA_t^i}$) is larger than the time control threshold ϵ_{TC}.

6.4.2 Monte Carlo Simulation

Scheduling methodologies can be assessed by running algorithm 1 a large amount of times by means of a Monte Carlo Simulation. In this Monte Carlo the starting positions r_0^i will be randomized. Also the winds are randomized as the methodology of determining W_t^i has a random component in it.

foreach $k \in \{1, .., K\}$ **do**
  Generate r_0^i randomly $\forall a^i \in A$ from a $U(R_{min}, R_{max})$-distribution
  Generate CI^i randomly $\forall a^i \in A$ from a $U(0, CI_{max})$-distribution
  Run algorithm 1
  $p^k = CF$
end
$\overline{CF} = \frac{\sum_{k=1}^{K} p^k}{K}$

Algorithm 2: Monte Carlo Simulation to assess the performance of scheduling methods.

$\overline{CF}$ from algorithm 2 is the average, or expected, performance of the assessed scheduling algorithm per flight. The aircraft sets A will be equal for all scheduling algorithms. This ensures that all algorithms have to deal with the same scenarios.

One point of attention is the fact that the used performance metric is the average over all flights, that have differing flight distances. This does not have an influence on the conclusions from this research for two reasons: Firstly, the testing scenarios for different scheduling methodologies will be identical as the random number generator that is used to generate the scenarios will be reset to the same value for every Monte Carlo Simulation. Secondly, the influence of differing flight distances gets averaged-out if K becomes sufficiently large because of the Law of Large Numbers.

Chapter 7

Scheduling Techniques

In this chapter currently existing scheduling techniques are discussed. The in chapter 6 described model then has to be expanded to take into account these techniques so that it can be validated. Then, a new technique should be developed and implemented into the model. This chapter will cover these steps and therewith form the basis of the results and outcomes of this research.

7.1 Current Scheduling Techniques

An early prioritization scheme came in the form of 'First-Come, First-Served' (FCFS) sequencing. Today, FCFS still is the main method of sequencing aircraft, as it is the simplest way to do so. For this reason it is the primary method being taught to aspiring ATCo's [36]. Despite its simplicity, it functions as a decent scheme assign limited capacity of airspace and runways to its users. [9]

In FCFS the aircraft that arrives first at the metering fix is cleared to land first. This means that if an aircraft follows-up on this aircraft within the minimal separation time, it has to be delayed. This delays the aircraft and burns off fuel. This problem is even worse when multiple aircraft arrive at the same time. In that case aircraft will typically be placed in a holding stack in the order they arrived at the metering fix.

A new method should be compared to FCFS to see what the improvement is (if there is any). The decision to compare it to FCFS is because of the widespread implementation of FCFS. As this research focusses at cost saving for airlines, techniques should be assessed based on the delays they induce (or mitigate) and the fuel usage of aircraft.

7.2 Simulating FCFS

The first of all scheduling techniques to be implemented will be FCFS. This will be done to assess the working of the simulation for validation purposes, as well as to have a benchmark to which other methods can be compared. The FCFS methodology lets aircraft that arrive at the target first land first. Other aircraft that are too close to the aircraft that is first to land (i.e. within the landing interval time of the leading aircraft) will be delayed. This delaying is typically done by placing them in a holding pattern or vectoring them to take a longer route, to delay their arrival.

Vectoring or flying holding patterns will be implemented synthetically in this simulation. This is done to avoid unnecessary complications. If an aircraft wants to land (or enter the fixing point) within the separation time of its preceding aircraft, it will keep its current position (i.e. its movement is 0), but will burn fuel at the normal rate during this waiting, and its flight time will also advance normally.

In the model FCFS has been implemented by letting aircraft maintain their coordinate if it arrives to shortly after a preceding aircraft has landed. During this time the flight time will advance normally even though the aircraft is not moved, and fuel burn is calculated as if were the aircraft to move normally.

Even though this is not the most realistic way to implement FCFS, as in reality the vectoring or placing in holding patterns will not take *exactly* the time that is required, as it is being issued by a human controller. In this simulation 'optimal' or 'ideal' vectoring is done, i.e. aircraft will only be delayed by the least possible time, and will only incur the minimally necessary amounts of time and fuel penalty. This means that the implemented functioning of FCFS is an optimal way of doing FCFS. This also means that any improvement in terms of time, fuel, and/or cost saving that can be realized from a newly developed methodology in the simulation, are likely to be bigger improvements in reality. In other words, it can be said that the efficiency of FCFS will be 'exaggerated' in the used implementation of it.

7.3 Ration-by-Schedule (RBS)

As one of the aims of this research is to compare scheduling algorithms it is useful to have multiple benchmarks. With FCFS one simple scheduling methodology is already available. To add to this also Ration-by-Schedule (RBS) will be considered as formulated by Brinton et al. in [39]. This algorithm can be found in algorithm 3.

```
Determine the slot times according to the specified maximum airport acceptance
  rate;
Sequence all flights in order of scheduled arrival time;
while ∃ Flights remaining do
  | Assign the next flight in the sequence to the earliest available slot that is at or
  |   later than the flight's scheduled time.
end
```

Algorithm 3: Ration by Schedule (RBS) Algorithm, adapted from [39]

According to Brinton et al. RBS performs better than FCFS. It is a deterministic scheduler as it assigns slots to aircraft by issuing CTAs to them. Aircraft then are forced to make this CTA, regardless of whether this is efficient for them. To keep RBS in line with the other algorithms in this research use will be made of ETA_0, i.e. the ETA at departure, as STA.

7.4 PTAs used to impose RTA restrictions to minimize overall costs

The scheduling algorithm aims to reduce the costs over the total duration of the flight, for all flights that are under consideration. The modelling algorithm assesses the scheduling algorithm using the function for total cost as given by Equation 6.8.

One of the fundamental cores of the method that is discussed in this report is that aircraft are given the freedom to fly their preferred speed as much as possible. The aircraft will do so by updating their Preferred Time of Arrival (PTA) continuously (within a certain tolerance), which is be handled by the FMS.

In addition to the already presented assumption that aircraft continuously try to minimize costs by controlling their speed, there are two additional assumptions:

1. Only in-flight delays (e.g. those due to wind) are considered. This is done by saving the first available Expected Time of Arrival, i.e. the ETA at the time the aircraft is first considered. This ETA will be referred to as ETA_0.
2. If an aircraft is imposed a CTA restriction, this will be handled by the FMS so that it becomes an RTA restriction. The FMS will then calculate a new flight speed to adhere to the restriction. This is also the case in real-life implementations ([38]).

7.4.1 Preferred Time of Arrival (PTA)

Given the assumptions above, aircraft will update their Preferred Time of Arrival (PTA) continuously, and will adapt their speeds also continuously - of course within the issued CTA limit -, depending on the wind conditions. From this it can be observed that the PTA is always the most cost-effective time of arrival for an aircraft, given its imposed restrictions. An algorithm to calculate the PTA for an aircraft is given in algorithm 4.

$$\begin{aligned} PTA_t^i &= pta(r_t^i, W_t^i, CI^i) \\ &= \min_k f^i(M^k * g_t^i) + (\frac{r_t^i}{M^k * g_t^i + W_t^i} - ETA^i_{Starttime})^+ * CI^i \end{aligned} \tag{7.1}$$

where $M^k \in \{M_{min}, M_{min} + 0.01, ..., M_{max} - 0.01, M_{max}\}$

Algorithm 4: Algorithm that calculates the Preferred Time of Arrival PTA_t^i, i.e. the arrival time that minimizes the total cost for aircraft a^i at time t by defining a function for PTA. Even though use has been made of g_t^i, i.e. the speed of sound for aircraft i at time t, this research will consider a constant speed of sound, so $g_t^i = g$.

The algorithm in algorithm 4 has the same outcome as the FMS that calculates the optimal flight speed given the flight plan and existing limits, the Cost Index and wind forecast.

It was shown for a small-scale problem in a thesis by Mitici ([4]) that direct operation costs for aircraft can be reduced if they are given more freedom to fly their desired speeds, while limiting them from interfering with eachother's arrival slot through the application of arrival time windows. The use of contracting, dynamic arrival time windows enables an arrival scheduling algorithm to not directly fix the exact arrival slots. Instead, aircraft are placed into time windows that are subdivided later on.

7.4.2 Defining Time Windows

In order to avoid the usage of holding patterns - which would have a negative impact on the gains from giving aircraft more speed freedom - it is needed to actively constrain aircraft from arriving in a time window that has too many arrivals. In order to effectively be able to ensure that not too many aircraft need to queue up for landing, it is first necessary to have a method to define the time windows. The aspect of uncertainty that is primarily under consideration in this study is the influence of wind on arrival time. Because it is (to a certain extent) uncertain what wind an aircraft may encounter in the future, the wind error simulation, as defined in chapter 5 is used as a basis.

In chapter 5 it was found that errors in wind predictions can be modelled with a normal distribution. One possibility would be to define windows by having as upper limit of the window the expected time of arrival if the aircraft were to encounter the maximum headwind, while not adjusting its speed. There are however two major flaws in this method: Firstly, considering every possible extreme of future wind is expected to create overly large windows which would result in an algorithm detecting conflicts that in reality have a negligibly small probability of occurrence. Secondly, as stated in section 7.4, aircraft will have the freedom (and are assumed to use this freedom) to capture delays if this is economical for them. In reality this will act as a 'damper' on the upper and lower limits of the ETA.

To take these observations into account it has been decided to introduce two parameters that control the size of the time window. These are α^+ and α^-. These parameters are the α^{th} quantiles of the wind error CDF, as is illustrated in Figure 7.1. From these parameters the upper and lower boundaries of the considered wind speed, $w(\alpha^+)$ and $w(\alpha^-)$ are found. This is also illustrated in Figure 7.1.

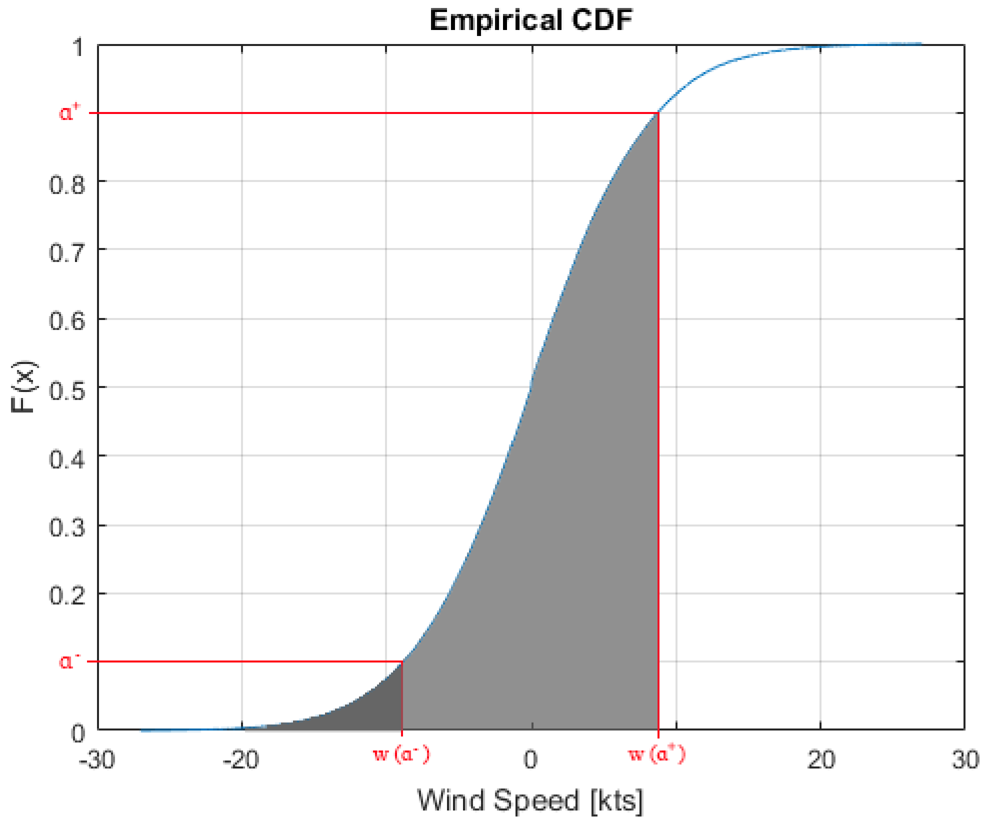


Figure 7.1: Illustration of the construction of $w(\alpha^+)$ and $w(\alpha^-)$.

The larger the difference between α^+ and α^- (it is sensible to have the parameters symmetric around 0.5), the larger the considered time windows will become. The found values for $w(\alpha^+)$ and $w(\alpha^-)$ are used as W_t^i in algorithm 4 to find the Earliest Landing Time (ELT) and Latest Landing Time (LLT), respectively. The ELT and LLT then serve as the lower and upper limits of the time window. So, $ELT_t^i = pta(r_t^i, w(\alpha^+), CI^i)$ and $LLT_t^i = pta(r_t^i, w(\alpha^-), CI^i)$.

The limits of the windows are being calculated in a way that is analogous to the calculation of PTA. This means that the windows get smaller as aircraft approach the target. Windows that have this property are called contracting windows. This property implies that fewer aircraft are considered close to the airport. This is beneficial as close to the airport, with a shorter distance to fly, there is less uncertainty about the ATA. Conversely, if a constant window size were to be considered, this would mean that too many aircraft are taken into account close to the airport.

Having defined the method to create the time windows, it is necessary to find a way to assign aircraft to them. It was noticed that capacities are stated in aircraft per time unit. Because the sizes of the constructed time windows will be subject to variation it does not make sense to fix the amount of aircraft per window. Instead, it is useful to look at the density of expected arrivals. To this end a new metric is introduced which is called the Density of Preferred Arrival Times (DPTA). The DPTA is defined according to

Equation 7.2. In this equation use is made of the indicator function $1_A : X \to 0, 1$ that yields 1 if $x \in A$, and 0 otherwise.

$$DPTA_t^i = \frac{\sum_{j=1}^{m} 1_{PTA_t^j \in [LLT_t^i, ELT_t^i]}}{LLT_t^i - ELT_t^i} \tag{7.2}$$

The DPTA is the density of PTAs in a given window that is limited by the ELT and LLT. Based on this metric a new scheduling algorithm is introduced in subsection 7.4.3 that aims to cost-effectively impose arrival time limits to aircraft by managing the DPTAs of the considered flights.

7.4.3 DPTA-Based Scheduling (DPTA-BS)

Given A being the set of aircraft available for landing, $A = \{1, ..., m\}$. Each aircraft a^i in set A has a Preferred Time of Arrival PTA_t^i according to algorithm 4. Algorithm 5 is a scheduling algorithm that aims to minimize the total costs for the aircraft it considers. The utilization of DPTAs lies at the core of this method, so the new method will be referred to as DPTA-Based Scheduling (DPTA-BS).

As stated, the algorithm makes use of Equation 7.2 to calculate the density in the arrival time windows which are bounded by the LLT and ELT. The algorithm looks at how many aircraft are intending to land within the same window, i.e. how many aircraft have their $ELT^i \leq PTA^j \leq LLT^i$. All these aircraft j form the set H_t^i. The density of the window is then calculated as $DPTA_t^i = \frac{|H_t^i|}{LLT_t^i - ELT_t^i}$.

Threshold Density D_{thres}

If the found value for $DPTA_t^i$ is lower than a certain threshold level D_{thres} this is deemed as being acceptable. If it is higher action should be taken.

D_{thres} should be chosen as such that $D_{thres} \geq C$. It can never be smaller than the stated capacity as this would create unnecessarily large spacing between aircraft. If D_{thres} is larger than the stated capacity more aircraft are allowed within a window than the runway can accommodate.

If a conflict is detected actions are taken by imposing CTA limits to aircraft in a cluttered window. This means that aircraft then have to fly at a non-optimal speed and hence incur a higher cost. Because of the uncertainty of wind speeds this means that aircraft may be unnecessarily made to change their speeds. To avoid the unnecessary imposing of limits a value for D_{thres} can be chosen that is higher than C.

On the contrary, D_{thres} should not be too high as this will result in not enough conflicts being detected, and the use of FCFS as last line of defence will be more prevalent. In fact, if $D_{thres} \to \infty$, DDTA-BS $\to$ FCFS.

Time resolution of DPTA-BS τ_s

This parameter is defined as being the interval between two runs of the DPTA-BS algorithm. The larger τ_s becomes, the less frequently it is run. If $\tau_s \rightarrow \infty$, DPTA-BS $\rightarrow$ FCFS as the algorithm will never be triggered. If τ_s is very large, but not infinite, as such that the DPTA-BS algorithm is triggered exactly once, in combination with $D_{thres} = 1$, the algorithm can be seen as a form of deterministic scheduler as it fixes the sequence in advance, and leaves no room for the influence of stochastic control. In fact, in this case DPTA-BS becomes Ration-by-Schedule as formulated by Brinton et al. in [39] (see algorithm 3 in section 7.3).

The DPTA-BS Scheduling Algorithm

If an aircraft is found that has a window which's density is too high, it has to be decided what action is taken. Clearly, the density in this window must be decreased by moving the PTA of one (or multiple) aircraft in the window to outside the window. To find the aircraft that experiences the smallest disadvantage from being moved to a non-optimal arrival time all possible resolution are calculated with a formula that is based on Equation 6.8.

This formula is evaluated for each aircraft in the window for PTA_t^j being both ELT_t^i and LLT_t^i. That aircraft that has the lowest value in this aircraft has the lowest cost from this formula then is being moved to either ELT_t^i or LLT_t^i, whichever is lowest. If the DPTA in the window then still is higher than D_{thres} the same procedure is repeated for the aircraft that are remaining in the window. If it is not possible to find a resolution for the conflict (e.g. when the aircraft with the overly-dense window is very close to the runway) nothing is done and FCFS will be used to determine the final arrival sequence.

while $D_t > D_{thr}$ **do**
  foreach *Aircraft* $a^i \in A$ **do**
    Calculate $ELT_t^i = PTA_t^i(r_t^i, w(\alpha^+), CI^i)$ with algorithm 4
    Calculate $LLT_t^i = PTA_t^i(r_t^i, w(\alpha^-), CI^i)$ with algorithm 4
    Let H_t^i be the set of aircraft a^j for which it holds that $ELT_t^i \leq PTA_t^j \leq LLT_t^i$
    $DPTA_t^i = \frac{|H_t^i|}{LLT_t^i - ELT_t^i}$
  end
  Let D_t be $max(DPTA_t^i)$ with corresponding H_t^i, ELT_t^i and LLT_t^i
  while $D_t > D_{thr}$ **do**
    foreach $a^j \in H_t^i$ **do**
      Calculate $CF^j_{ELT_t^i}$ and $CF^j_{LLT_t^i}$, i.e. the cost functions if ETA_t^j is set to equal ELT_t^i and LLT_t^i, respectively.
    end
    Find the lowest $CF^j_{ELT_t^i}$ and $CF^j_{LLT_t^i}$ from the previous foreach loop. Denote these as $CF_{ELT,min}$ and $CF_{LLT,min}$, respectively.
    if $CF_{ELT,min} < CF_{LLT,min}$ **then**
      Impose the limit to aircraft a^j (j corresponds to $CF_{ELT,min}$) that it cannot land after ELT_t^i, i.e. set $CTA_t^j = ELT_t^i$.
    if $CF_{ELT,min} > CF_{LLT,min}$ **then**
      Impose the limit to aircraft a^j (j corresponds to $CF_{LLT,min}$) that it cannot land before LLT_t^i, i.e. set $CTA_t^j = LLT_t^i$.
    else
      Do nothing and break from while-loop.
    end
    $D_t = D_t - \frac{1}{LLT_t^i - ELT_t^i}$
  end
end

Algorithm 5: The DPTA-BS scheduling algorithm that makes use of the Density of Optimal Arrival Times (PTAs).

Illustration of algorithm 5

To illustrate the working of algorithm 5 several short examples will be given. The examples will only take into account small numbers of aircraft, whereas in reality, the algorithm will (possibly) be dealing with large amounts of aircraft.

Example 1: Low Window Density

In Figure 7.2 a schematic view of three aircraft that intend to land with minimal cost can be found. The aircraft are 50km apart, with the middle one being 2500km away. The middle aircraft has the intention to land at noon, the other 2 aircraft intend to land three minutes earlier and later. All aircraft have the same CI. Further, $C = 60$ ac/hr and $D_{thr} = 1.5 * C$.

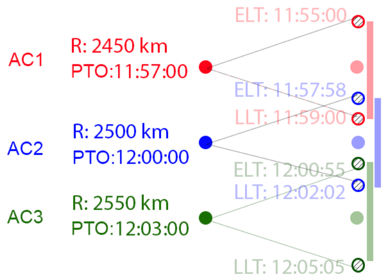


Figure 7.2: Example 1

In Figure 7.2 the windows have been drawn for $(\alpha^-, \alpha^+) = (0.25, 0.75)$. Even though there is some overlap of the windows of the three aircraft, all windows have only one PTA in them, which means that $DPTA^1 = DPTA^2 = DPTA^3 = 1 \leq 1.5$. Hence, the density of all windows falls below the threshold capacity, and no action is taken.

Example 2: Medium Window Density

In Figure 7.3 again a schematic overview of three aircraft can be found. All is the same as in Example 1, except that now the closest aircraft is 2480 km away from the target, instead of 2450 km in Example 1.

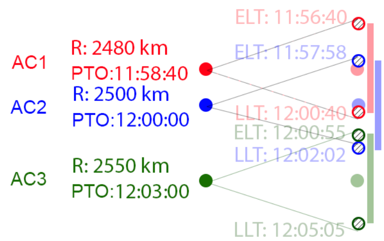


Figure 7.3: Example 2

Now the first and the second aircraft fall within eachother's windows, so $|H^1| = |H^2| = 2$. $DPTA^1 = \frac{2}{(12{:}00{:}40 - 11{:}56{:}40)} = 0.5$ ac/min and $DPTA^2 = \frac{2}{12{:}02{:}02 - 11{:}57{:}58} = 0.495$ ac/min. Both windows are below the limit of $D_{thr} = 1.5$ ac/min, so no action is taken.

Example 3: Excessive Window Density

In Figure 7.4 another schematic of three aircraft can be found. It can be seen of the evolution after some hours of Example 2. The closest aircraft has been delayed a slight bit, so that it now has its optimal time only 20 s before the optimal time of the middle aircraft. The farthest aircraft has had some delay and is now several minutes behind the first two, and is no longer in any of their windows. As in Example 2, $|H^1| = |H^2| = 2$. The densities this time are: $DPTA^1 = \frac{2}{(12{:}00{:}16 - 11{:}59{:}04)} = 2.5$ ac/min and $DPTA^2 = \frac{2}{12{:}00{:}36 - 11{:}59{:}24} = 2.5$ ac/min. Both densities are larger than D_{thr}, so action is necessary.

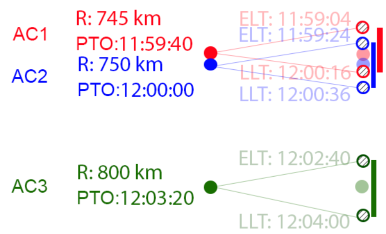


Figure 7.4: Example 3

The two densities appear to be equal because of rounding errors; Because the window of the closest window is ever so slightly shorter than that of the middle, the closest window has a higher density than the middle window. Because the density of the closest window is the largest, that is the window that is first considered in algorithm 5.

Now, two quantities need to be calculated, namely the costs for the Red aircraft if it were to have its $CTA^1 = ELT^2$, and the costs for the Blue aircraft if it were to have its $CTA^2 = LLT^1$. It appears that the costs are as follows (the reader is kindly reminded that all aircraft have the same $CI = 300$): $CF(a^1|CTA^1 = ELT^2) = 21,099.52$ and $CF(a^2|CTA^2 = LLT^1) = 21,240.93$. The cost for speeding up the Red aircraft is lower than for slowing down the Blue aircraft, so that is the solution that is proposed.

Thanks to the resolution the density in the middle window reduces because now only 1 aircraft is present, and coincidentally the density in the first window also reduces because also there now only 1 aircraft is present.

Chapter 8

Results

Having established a testing methodology in chapter 6 and designed a new scheduling algorithm in chapter 7, this chapter will delve into the performance of DPTA-BS. It will be compared to FCFS and Ration-by-Schedule (RBS).

This chapter is structured as follows: In section 8.1 the model parameters will be chosen and justified. In section 8.2 the model will be tested for different levels of utilization. In section 8.3 the sensitivity of the DPTA-BS parameters will be studied. A conclusion can be found in section 8.4.

8.1 Parameter Choices

Before the simulations can be performed it is necessary to define the setting parameters for the simulation. In this section each parameter choice will be discussed, as well as its impact on the result. There are two types of parameters: model parameters that define the working of the model, and algorithm parameters that define the working and choices of the algorithm. The model parameters will be (with the exception of amount of aircraft) kept constant across the different runs. The algorithm parameters will be subject to a sensitivity analysis to discover a suitable set of setting parameters for the algorithm.

8.1.1 Model Parameters

First the model parameters will be discussed. The model parameters are the amount of Monte Carlo runs K, the minimum and maximum flight distances R_{min} and R_{max}, the amount of aircraft per run m, the arrival capacity C and the minimum and maximum cost index CI_{min} and CI_{max}. An overview of the chosen parameters can be found in Table 8.1. The justifications for these choices can be found below. The setting parameters for the wind model can be found in chapter 5.

Table 8.1: Chosen Model Parameters. These are constants for all simulations done in this research.

K [#runs]	10000
R_{min} [km]	0
R_{max} [km]	5000
C [#ac/hr]	60
CI_{min} $[kg/min]$	0
CI_{max} $[kg/min]$	587
τ_w [min]	5

Amount of Monte Carlo runs: K

The parameter that specifies the amount of runs the Monte Carlo simulation does is K in algorithm 2. One Monte Carlo run is one run of the simulation in algorithm 1.

Because a Monte Carlo simulation is used, there is a certain form of uncertainty in the results. To estimate the uncertainty of the results it is possible to get a 2σ-confidence interval by adding and subtracting $\frac{1.93\sigma}{\sqrt{K}}$ to the found mean. It was found that at 10000 runs this value tends to be below 50 [kg], which is enough to ensure validity of the results. The time that one Monte Carlo simulation takes is approx. 2 hours [1]. On the system that is used for this research four Monte Carlo runs can be run simultaneously, meaning that 20 different parameter settings can be tested in 10 hours.

Minimum and Maximum Flight Distance: R_{min} **and** R_{max}

The minimum and maximum flight distance choices specify the range for generation of new aircraft. The aircraft are generated according to $U(R_{min}, R_{max})$ uniform distribution. It has been decided to take a flight distance between 0 and 5000 km. The choice of 0 as minimum has been made to include also aircraft that are already close to the airport without being considered by a scheduler. As aircraft fly at approx. 850 km/h the choice of 5000 km for the upper limit means that flights will be up to 6 hours long.

If aircraft are generated closely to eachother (i.e. at a similar distance away from the target) no specific actions are taken to get these aircraft away from eachother. Firstly, there is no in-flight separation. Secondly, either DPTA-BS or FCFS are tasked to deal with this at the target.

Capacity: C

The amount of aircraft that are simulated in one run of the Monte Carlo is defined by m. This parameter has a strong connection to the choice of R_{min}, R_{max} and the arrival capacity C. This is the case as the combination of flight time and amount of aircraft influence the average inter-arrival rate at the IAF, which should not exceed the arrival capacity to avoid excessive queueing.

[1] Depending on choices of the other parameters this can be longer or shorter. The simulation takes roughly 2 hours for the parameter choices in this chapter

Typical runway capacities are around 45 aircraft per hour according to Kern et al. in [37]. To facilitate the testing under differing capacity utilization levels of the model it has been decided to make use of a capacity of 60 aircraft per hour, or one aircraft every minute. This choice will not have any influence on the conclusions of this research as newly developed algorithms will be compared to state of the art methods at the same capacity setting. The validity of this choice has been checked in chapter 9.

Given the fact that aircraft are uniformly distributed over a 5000 km distance, the flights are up to approx. 6 hours long. This means that $6 * 60 = 360$ aircraft can be handled without exceeding the stated capacity on average. In section 8.2 the performance of DPTA-BS will be analysed under different capacity utilization levels.

Minimum and Maximum Cost Index: CI_{min} and CI_{max}

The cost index plays a central role in this research as it both influences the flight speed which influences scheduling, as well as the cost of a flight which influences the assessment of the performance of the algorithm.

Given that the fuel model that is used in this research has been calibrated for a Mach-range between 0.75 and 0.86 the CI limits are chosen so that it is assured that the flight speed falls in the Mach-range. As $M = 0.75$ minimizes the fuel usage per flight distance this is the Mach number corresponding to $CI = 0$ (by definition). The maximum Mach number is reached at $CI = 587$. It has been chosen to set $CI_{max} = 587$ to ensure that aircraft always have the possibility at the onset of the flight to reach the target at a cost that is equal to their benchmark.

Wind Update Interval Time: τ_w

The wind update interval time defines how often the wind speeds will be generated for the aircraft. This means that the wind speeds for the aircraft in the simulation will be updated every 5 minutes. In reality this happens continuously. As the model has been calibrated for updates every 5 minutes, it has been chosen to have $\tau_w = 5$ minutes.

8.1.2 DPTA-BS Parameters

Having discussed the model parameters, the attention now is turned to the setting parameters of the newly developed algorithm. These parameters influence the way how the algorithm does its work. To a suitable set of setting parameters for the algorithm a sensitivity analysis will be done. The testing range for each parameter can be found in Table 8.2. In this table also the step size for each parameter can be found. Note that the sensitivity analysis will be performed for all three different choices of amount of aircraft per run in Table 8.1.

Table 8.2: Chosen ranges and step sizes of DPTA-BS algorithm parameters.

Parameter	Range	Step Size
D_{thres} [#AC/min]	1.0 - 5.0	0.5
(α^+, α^-)	(0.1,0.9) - (0.3,0.7)	0.1
τ_s [min]	10 - 30	10

Threshold Density: D_{thres}

The threshold density D_{thres} is the acting threshold for the density of a window: If the density is higher than the threshold density, the algorithm will act on it.

It may be tempting to pick the threshold density equal to the arrival capacity, as it will then never occur that too many aircraft arrive at the airport, and queueing is avoided. Due to the uncertain nature of disturbances during the flight however, this is not expected to be an optimal choice. Instead, a higher value should be chosen to still allow some overlap, which may lead to some queueing, while avoiding excessive controlling of aircraft speed. This will avoid ping-ponging between slots. Obviously, D_{thres} should never be smaller than C.

It has been decided to test D_{thres} ranging from $1.0 * C$ to $5.0 * C$ at 0.5 increments.

Window Size Setting Parameters: α^- **and** α^+

The window size setting parameters α^- and α^+ define the size of the window as these parameters define the range of wind speeds that will be taken into account. It has been decided to keep α^- and α^+ symmetric around 0.5. Three settings will be tested for (α^-, α^+): $(0.1, 0.9)$, $(0.2, 0.8)$ and $(0.3, 0.7)$. For an illustration of the influence of choices for α^- and α^+ the reader is kindly referred to Figure 7.1.

Schedule Update Time: τ_s

How often the algorithm is used to update the schedule is defined by τ_s. The more frequent the algorithm is run, the more often changes are made to the schedule. It is expected that more frequent execution of the algorithm will improve its performance. There is however a practical lower limit as any changes in flight speed will have to be executed by the ATCOs and pilots, which will induce a delay time. Even though this delay time is not modelled, it will be taken into account by not having τ_s smaller than 10 minutes. Instead, τ_s will be chosen to be between 10 and 300 minutes, with step sizes of 10 minutes. As an additional consideration it is important to take into account the time that is needed to run one simulation: a very small value for τ_s will drastically increase the required computation time of the simulations which leads to practical burdens for the research.

8.2 Results for Differing Capacity Utilization Levels

An important aspect in the assessment of scheduling algorithms is their performance under different capacity utilization levels. The capacity ($C = 60$ ac/hr) is a constant parameter. The extent to which the capacity is met on average is called the capacity utilization level and is a percentage of capacity. If, e.g. the utilization level is 75% of C this means that on average 45 aircraft land per hour. In the developed model this means that 270 aircraft are generated per Monte Carlo run (75% of 360).

To evaluate the performance of the algorithm it will be tested under different utilization levels. As the utilization level is differed the algorithms are expected to perform differently. The algorithm will be tested at utilization levels between 25% and 100% of the arrival capacity, at 5pp intervals.

In addition to the in section 6.3 developed cost function a look will be taken at the percentage of outperformance of DPTA-BS w.r.t. FCFS. To do this, for each of the scenarios in the Monte Carlo simulator the performance under FCFS and DPTA-BS of the same scenario will be compared, and the amount of times that DPTA-BS outperforms FCFS will be counted. This can be used to calculate the percentage of outperformance over all K runs. The used equation is given in Equation 8.1.

$$PoO = \frac{\#\text{ times DPTA-BS performs better than FCFS} \in K}{K} * 100\% \tag{8.1}$$

If the found percentage is significantly higher than 50% it can be said that DPTA-BS outperforms FCFS in a majority of the cases (at the respective percentage of capacity). If it is significantly lower than 50% it can be said that FCFS outperforms DPTA-BS. If there is no significant deviation from 50% it can be said that it is indifferent whether FCFS or DPTA-BS is used as it is split (almost) fifty-fifty. In other words, the found percentage can be seen as the probability that DPTA-BS outperforms FCFS in a case, given the utilization level.

To test statistical significance use will be made of the Students T-Test on the difference of DPTA-BS w.r.t. FCFS. This test tests the null-hypothesis (H_0) that the mean of a normally distributed sample is 0. If, given a significance level this null-hypothesis is rejected it must be concluded that the mean of the sample is non-zero, or in this specific case, that the used samples of DPTA-BS and FCFS have different means. A significance level of 5% will be used.

It is expected that at lower load cases there will be the performance of DPTA-BS will be close to that of FCFS. This is the case as DPTA-BS is based off FCFS and adjustments are only triggered if the density of expected arrivals within a window exceeds a limit (the threshold capacity D_{thres}, which is a setting parameter of the DPTA-BS algorithm). Therefore, at lower load cases, where, on average, there will be fewer aircraft per unit of time, the algorithm will be triggered less frequently. At higher loads the algorithm will be triggered more frequently, and its optimization take place more frequently.

In addition, it is expected for lower load cases that the percentage of outperformance for DPTA-BS w.r.t. FCFS is close to 50%, as in these cases the algorithm is triggered less frequently. For higher load cases however, it is expected that the percentage of outperformance is significantly larger than 50%.

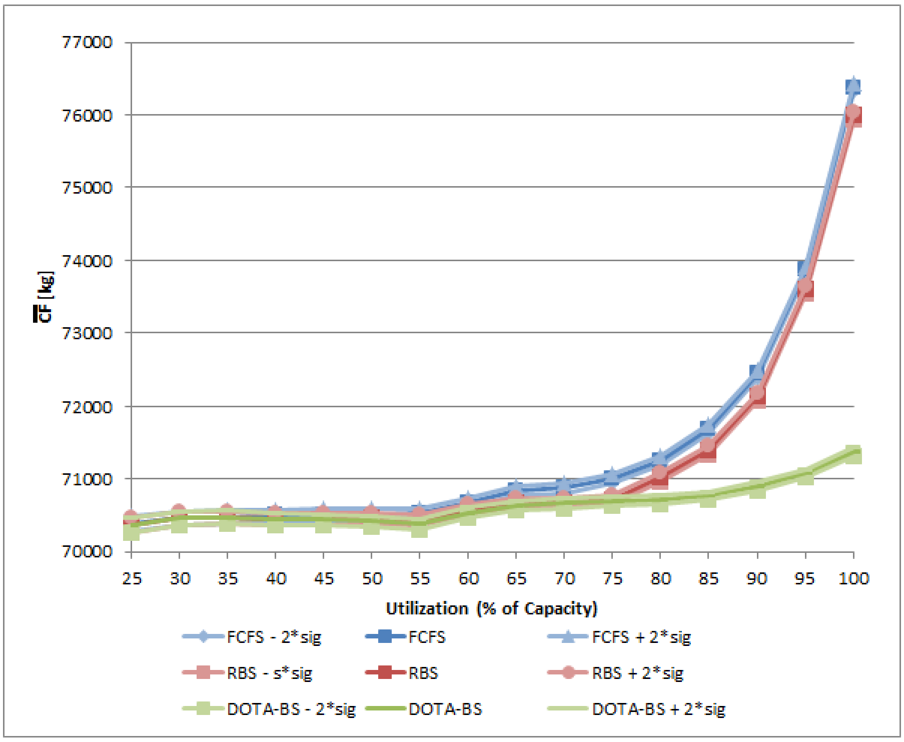


Figure 8.1: Average cost and confidence intervals of DPTA-BS, FCFS and RBS over 10000 runs. $C = 60$ ac/hr, $D_{thres} = 2C$, $(\alpha^+, \alpha^-) = (0.10, 0.90)$, $\tau_s = 30$ mins. The detailed results can be found in tables A.1-A.3 in Appendix A.

It can be seen clearly for higher arrival loads that RBS has a lower average cost than FCFS, and that DPTA-BS has a lower cost than the former two. It is however difficult to see what happens at lower utilization levels. To this end the detailed results of RBS and DPTA-BS can be found in Appendix A. It appears that at the lower utilization levels the average performance of DPTA-BS, FCFS and RBS are close to eachother. This is because at these levels the aircraft are not often close enough to affect eachother.

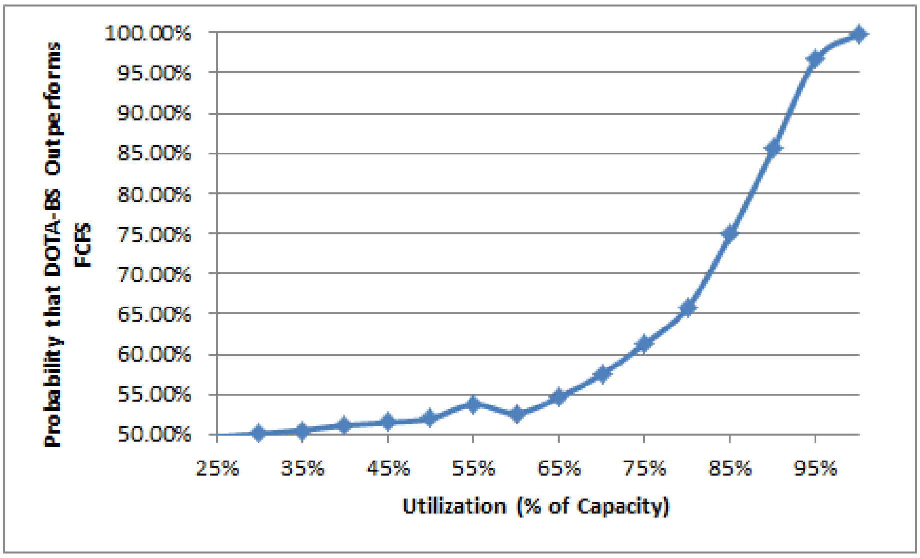


Figure 8.2: Empirical probability of outperformance (according to Equation 8.1) of DPTA-BS w.r.t. FCFS over 10000 runs. $C = 60$ ac/hr, $D_{thres} = 2C$, $(\alpha^+, \alpha^-) = (0.10, 0.90)$, $\tau_s = 30$ mins.

In addition to average performance under increasing load cases, a look was taken at the frequency of outperformance of DPTA-BS w.r.t. FCFS. The percentage of times DPTA-BS outperformed FCFS over 10000 runs has been plotted in Figure 8.2 for increasing load cases. It can be seen that at lower load case DPTA-BS only has a marginal edge over FCFS, frequency-wise. As the arrival load increases, however, the probability of outperformance rises to nearly 100% at 100% of capacity.

The given results are the resultant of a Monte Carlo simulation that made use of random generations of aircraft scenarios and winds. Because of this it is necessary to take into consideration the confidence interval of the established results.

To illustrate this approach a close look will be taken at the results at 85% of the runway capacity. For 85% the DPTA-BS has a performance that is 919 [kg] better than FCFS per aircraft. When doing a sample t-test on the differences between FCFS and DPTA-BS to test the null hypothesis (H_0) that the mean of the sample is zero at a 5% confidence level, it is found that this hypothesis is rejected. The found p-value is 0. Because of this it can be said for an 85% of capacity case that DPTA-BS outperforms FCFS by a significant margin. The found p-values from the t-test can be found in Table 8.3.

Table 8.3: Found p-values from t-tests for zero means among FCFS, RBS and DPTA-BS at a 5% significance level at 85% of capacity.

	t-test p-value
FCFS, RBS	5.3×10^{-45}
FCFS, DPTA-BS	0
RBS, DPTA-BS	0

For the lower arrival loads the t-test does not reject H_0. This means that there is a possibility that, at lower load cases DPTA-BS performs worse than FCFS.

The used cost function $\overline{CF}$ is the cost of fuel and time, where time is converted to fuel weight through the cost index. The overall cost reduction is thus due to a combination of changes in fuel usage and delays. To assess this difference a look is taken at the 90% utilization case at the average flight time and average fuel usage w.r.t. FCFS. The found results can be found in Table 8.4.

Table 8.4: Average fuel usage and flight time per aircraft from a Monte Carlo simulation with $K = 10,000$, $D_{thres} = 2$, $\tau_s = 30$ min, and $(\alpha^-, \alpha^+) = (0.1, 0.9)$ at a utilization level of 90%.

	Fuel/ac [kg]	T/ac [s]
FCFS	$20,997 \pm 40.7$	$10,521 \pm 20.2$
DPTA-BS	$20,557 \pm 40.4$	$10,298 \pm 20.1$

It can be seen in Table 8.4 that DPTA-BS saves both time and fuel. The savings are 2.1% for both the average fuel per flight and average time per flight.

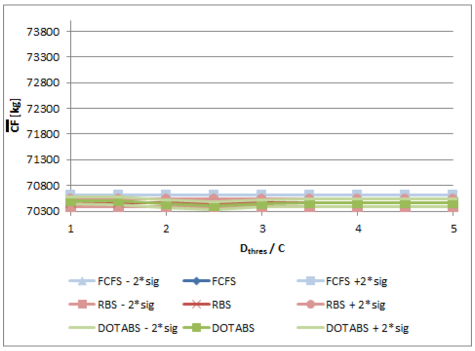
8.3 Sensitivity of DPTA-BS Parameters

Based on the setting parameters for the sensitivity analysis described in subsection 8.1.2, this section will present and discuss the results. It will be split into 3 subsections: firstly, the sensitivity of the DPTA-BS algorithm for changes in D_{thr} will be discussed in subsection 8.3.1. Thereafter, the sensitivities of τ_s and (α^-, α^+) will be discussed in subsections 8.3.2 and 8.3.3, respectively.

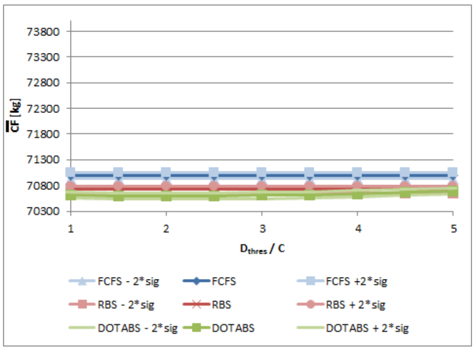
In each of the different subsections the performance of the DPTA-BS algorithm will be compared to FCFS. For each parameter 10000 scenarios of 180 aircraft (50% of Capacity), 270 aircraft (75% of Capacity), 324 aircraft (90% of Capacity) and 342 aircraft (95% of Capacity) are created. Based on these scenarios the model is run for FCFS, RBS and DPTA-BS. To assess the performance of the algorithms use is made of the cost function $\overline{CF}$ in Equation 6.8.

8.3.1 D_{thres}

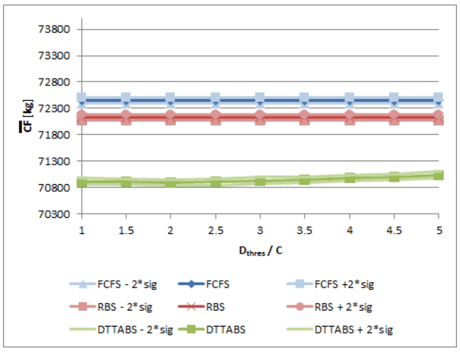
The results for the sensitivity study for D_{thres} can be found in Figure 8.3.



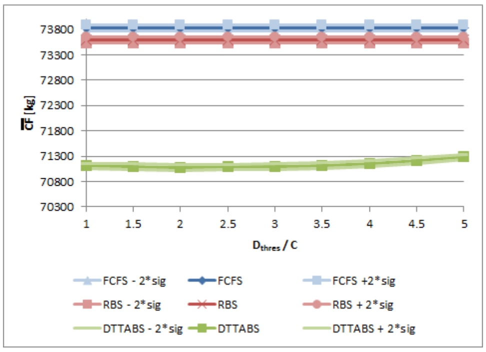
(a) 50% Utilization



(b) 75% Utilization



(c) 90% Utilization



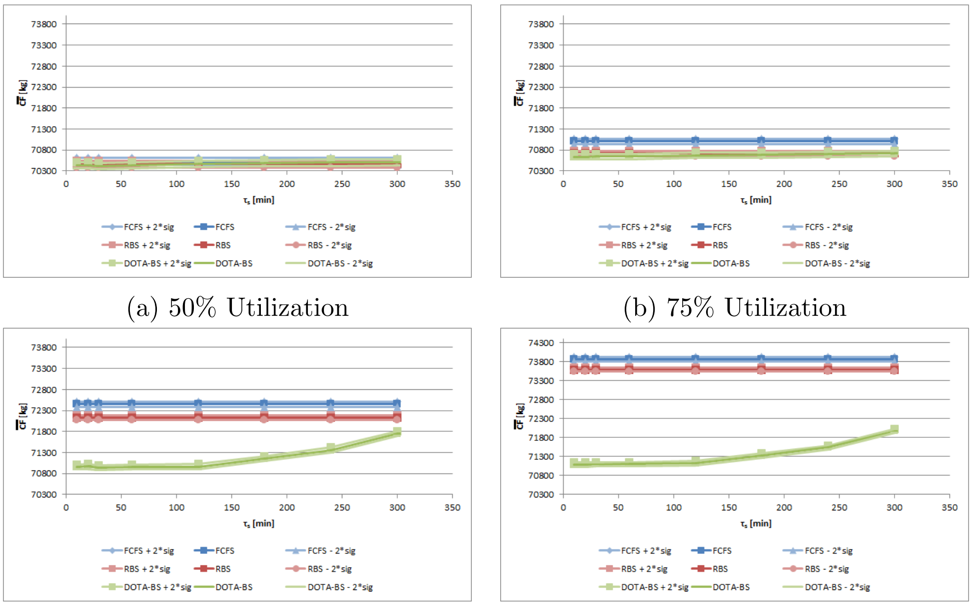
(d) 95% Utilization

Figure 8.3: Results and upper and lower confidence intervals (2σ) of the results for differing values of D_{thres} with utilization at 50%, 75%, 90% and 95% of capacity. Also indicated are the means and confidence intervals of FCFS and RBS. $C = 60$ ac/hr, $(\alpha^-, \alpha^+) = (0.1, 0.9)$ and $\tau_s = 30$ mins. The detailed results can be found in tables A.4-A.11 in Appendix A.

In Figure 8.3 it can be seen that the behaviour for different values of D_{thres} is similar for different utilization levels. The primary difference is that for higher levels there is a significant outperformance for DPTA-BS w.r.t. RBS across the D_{thres} range. It appears that under all choices for D_{thr} DPTA-BS performs better than FCFS. DPTA-BS seems to perform best in the given aircraft density at a setting of $D_{thr} = 2$. There is a rapid drop off in performance when D_{thr} is increased beyond a certain level. This is because the algorithm will be triggered less frequently, leaving some of the potential not utilized. If D_{thr} is smaller than 2 it seems to have an impact on its performance. This can be explained by considering that more speed changes will be issued when a lower value is chosen. This increases the chance of unnecessary speed changes. At higher values for D_{thres} the cost of DPTA-BS gets closer to that of RBS.

8.3.2 τ_s

The results for the sensitivity study for τ_s can be found in Figure 8.4.



(a) 50% Utilization

(b) 75% Utilization

(c) 90% Utilization

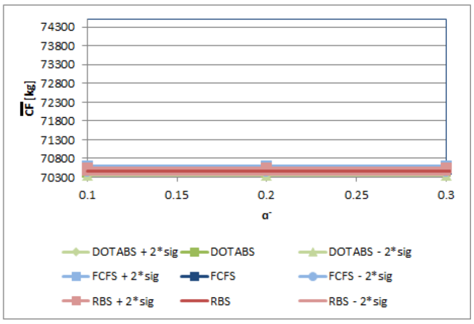
(d) 95% Utilization

Figure 8.4: Results and upper and lower confidence intervals (2σ) of the results for differing values of τ_s with utilization at 50%, 75%, 90% and 95% of capacity. Also indicated are the means and confidence intervals of FCFS and RBS. $C = 60$ ac/hr, $(\alpha^-, \alpha^+) = (0.1, 0.9)$ and $D_{thres} = 2$. The detailed results can be found in tables A.12-A.15 in Appendix A.

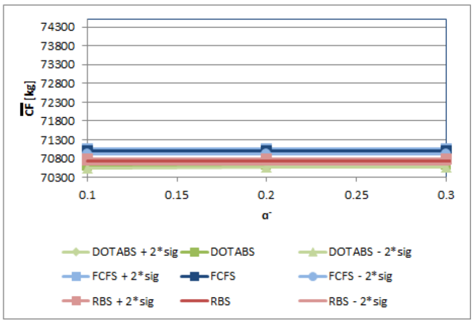
In Figure 8.4 the performance of DPTA-BS under different choices for τ_s can be found. It is noticed that as τ_s increases (and thus the amount of times that DPTA-BS is run reduces), the performance deteriorates w.r.t. FCFS and RBS drastically. This indicates that if the continuous evaluation aspect of DPTA-BS is reduced, its effectiveness reduces, too. This indicates that part of the performance gain that DPTA-BS has results from the fact that it is evaluated on a regular basis. In addition it can be seen there there is not a significant performance drop-off if DPTA-BS is run every 120 mins. It can therefore be recommended for a real-world implementation to use this for τ_s instead of 30.

8.3.3 (α^-, α^+)

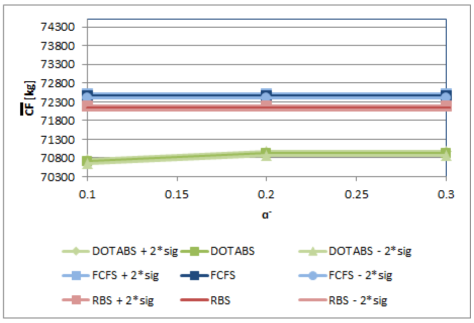
Now leaving D_{thres} and τ_s constant we look for the impact of changes in (α^-, α^+). As stated in subsection 8.1.2 the choice for (α^-, α^+) will be symmetric around 0.5 at 0.1 intervals. This means that the tested values are: $(0.1, 0.9)$, $(0.2, 0.8)$ and $(0.3, 0.7)$. For $D_{thres} = 2$ and $\tau_S = 30$ min. The resulting graph can be found in Figure 8.5.



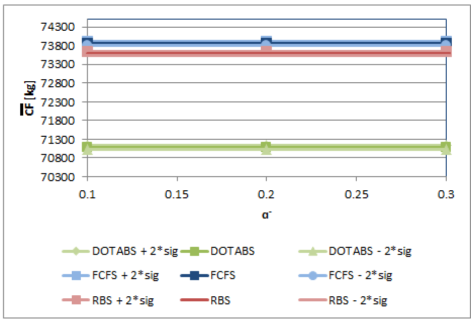
(a) 50% Utilization



(b) 75% Utilization



(c) 90% Utilization



(d) 95% Utilization

Figure 8.5: Results and upper and lower confidence intervals (2σ) of the results for differing values of α^- with utilization at 50%, 75%, 90% and 95% of capacity. Also indicated are the means and confidence intervals of FCFS and RBS. C = 60 ac/hr, τ_s = 30 min and D_{thres} = 2. The reader is kindly reminded that a value of $\alpha^- = 0.1$ corresponds to $\alpha^+ = 0.9$ as the α's are chosen symmetrically around 0.5. The detailed results can be found in tables A.16-A.19 in Appendix A.

It can be seen that for all chosen values[2] DPTA-BS outperforms FCFS by a significant margin. This implies that DPTA-BS tends to outperform FCFS no matter the choice of α. It seems that a higher α^-, i.e. smaller window sizes, has a worse performance than if α^- is smaller, even though the difference is small.

8.4 Conclusion

Based on the results that were presented and analysed in this chapter it can be concluded that DPTA-BS outperforms FCFS and RBS at higher utilization levels. It can be concluded that at these higher levels DPTA-BS provides a significant edge over the two scheduling methods it was compared to.

It was also found from a broader sensitivity analysis that a reduction of the amount of times that DPTA-BS is used to re-evaluate a schedule deteriorates the performance. This indicates that part of the performance gain that is attained by DPTA-BS is attributable to the fact that it is used on a regular (near-continuous) basis, whereas RBS is used only once.

[2]Having $\alpha^- = 0.1$ means that $\alpha^+ = 0.9$ as the values are symmetric around 0.5.

Chapter 9

Verification

To ensure that the results from this research can be used to draw conclusions w.r.t. the performance of scheduling techniques, it is necessary to verify the working of the model and validate the results. The verification will be done in this chapter in a total of two steps: firstly, the individual components of the simulation model, and the model as a whole, will be verified in section 9.1. Secondly, the working of the algorithms (both FCFS and DPTA-BS) will be verified in section 9.2. During the verification it will be checked whether the *"model implementation and its associated data accurately represent the developers conceptual description and specifications."* This is in accordance with the definition of verification according to [40].

9.1 Model Verification

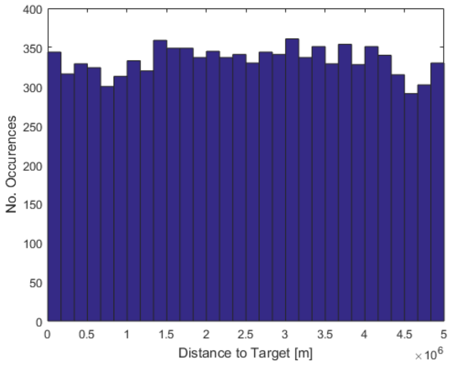
To verify the model it is important to first verify the working of the individual (sub)components of the model. First the aircraft generator will be verified in subsection 9.1.1. Then, the component that keeps track of the aircraft as time progresses in the simulation is validated in subsection 9.1.2.

9.1.1 Aircraft Scenario Generator

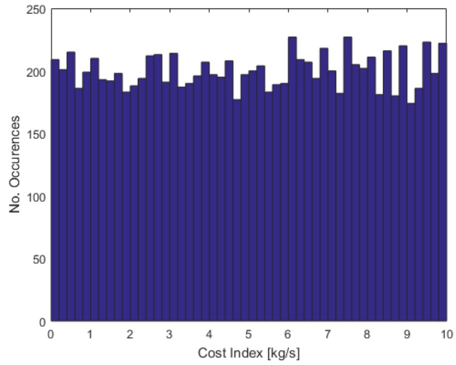
The task of the Aircraft Scenario Generator is to generate scenarios of aircraft. It has to come up with two random variables per aircraft. The first is the distance the aircraft is away from its target. The second is the cost index.

The distance is drawn from a $U(R_{min}, R_{max})$-distribution, where R_min and R_max are the lower and upper limits of the distance an aircraft still can fly, respectively. Also the CI is drawn from a uniform distribution, but then between the minimum and maximum values for the cost index. To ensure consistency in units it has been decided to have the entire simulation in SI-units. This must hence also be applied to the limits of the sampling distributions. In Figure 9.1 the histograms for CI and distance from the target for 10000 aircraft can be found.

No oddities can be found in the histograms in Figure 9.1 and the found histograms are close to uniformly distributed. Therefore, it can be concluded that the Aircraft Scenario Generator works as intended.



(a) Histogram of distances to target for 10,000 aircraft from the ASG.



(b) Histogram of cost indices for 10,000 aircraft from the ASG.

Figure 9.1: Histograms of generated CIs and distances from the Aircraft Scenario Generator.

9.1.2 Aircraft Tracker

The Aircraft Tracker maintains the aircraft and assures that they fly around and get the appropriate time and fuel usages. Also, it calculates the total cost function based on Equation 6.8. This paragraph will check the appropriate calculation of location, and the total fuel usage. Finally the correctness of exclusion of landed aircraft will be verified.

When disabling speed alterations during the flight, and disabling wind effects, it is easy to verify the consistency of time and fuel, while taking into account the exclusion after landing. In such a case aircraft will fly at a constant ground speed given their constant Mach number. Also, as aircraft are allowed to land simultaneously, the capacity goes to infinity, and the aircraft will be excluded from the analysis the instant they reach the target.

After a single simulation of 100 aircraft, without separation criteria active, and a cut-off distance of 0 m (i.e. aircraft are no longer considered if their distance to the target is 0m or less), it is found that all distances to the target are between -2.37 m and -247.56 m. All values are negative because aircraft are only excluded if they have passed the target. The smallest value, -247.56 m, occurs for a flight with $M^i = 0.84$, right at the top of the Mach-range. The distance this aircraft can fly during one time step of the simulation (dt = 1s) is $M * a * dt = 0.85 * 299.46 * 1 = 254.54$. This is larger than the found value of 247.56 m, so the implementation of the cut-off distance works as it should.

This aircraft had a starting position that was 2,188,073 m from the target. It's flight time was 8741s at $M = 0.84$, consuming 18267kg of fuel. Flying for 8741s at $M = 0.84$ yields a distance of $M * a * t = 0.84 * 299.46 * 8741 = 2,198,791$. This is approx. 0.45% more than the starting distance. This is acceptable given rounding errors in M and a.
The fuel usage is calculated for each time step in the simulation. Calculating the fuel usage for the entire duration of the flight at $M = 0.84$ in one go yields a result of 18,597kg, which is 1.81% more than the given value of 18,267kg. Again, given rounding errors in M this is acceptable. Similarly sensible results were obtained if a constant wind speed was taken into account. This verifies the correct inclusion of wind speeds.

This concludes the verification of the testing model.

9.2 Scheduling Algorithm Verification

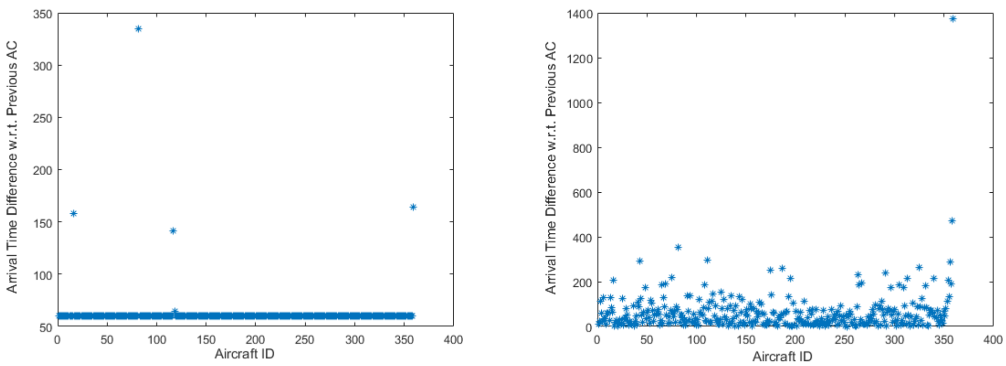
Having verified the working of the model, it is now time to verify the working of the implementations of the scheduling algorithms. Firstly, FCFS will be verified in subsection 9.2.1. Secondly, the in chapter 7 developed DPTA-BS algorithm will be verified in subsection 9.2.2.

The results from the model with the algorithms in place will be analysed to verify the correctness of their working. This will be done in different ways, dependent on the algorithm.

9.2.1 FCFS

To verify whether FCFS is implemented correctly, it will be verified that there are no aircraft with inter-arrival times that are smaller than the minimum separation time at the fixing point. Also, the performance metric should be higher than for the case when the inter-arrival time is reduced to 0. This represents the hypothetical situation that aircraft can land simultaneously, the so-called infinite capacity case.

Firstly, it appears from an analysis that the inter-arrival time under FCFS is not smaller than 60s for a single run with 360 aircraft. A plot of the inter-arrival times can be found in Figure 9.2a. As can be seen in the plot, the inter-arrival times for nearly all flights is 60s. This is because of the choice of 360 aircraft, which means that the capacity is, on average, exactly met. When comparing this to Figure 9.2b, where the same plot is given for a simulation without any separation criteria, there is a larger spread in inter-arrival times. A considerable amount of inter-arrival times is smaller than 60s in this case.



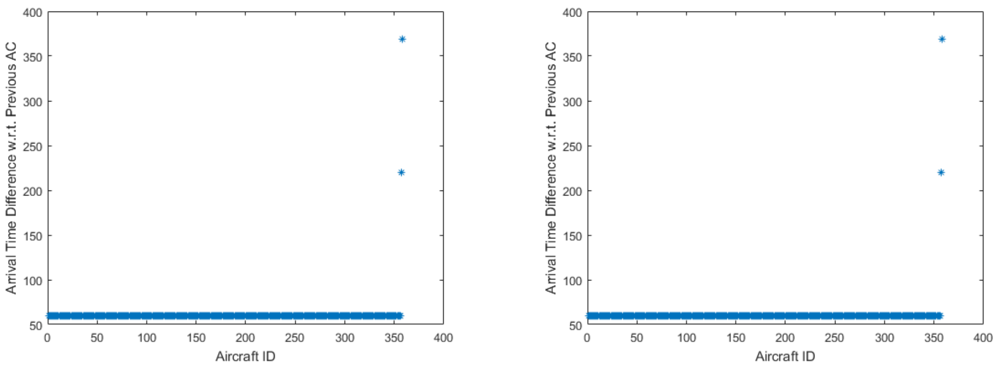
(a) (b)

Figure 9.2: Plots of inter-arrival times of a single run of 360 aircraft (this corresponds to a utilization level of 100%). In Figure 9.2a the plot is given for FCFS with a separation minimum of 60s; In Figure 9.2b the same plot is given where the separation minimum is 0s.

Further, when comparing the total cost metrics for FCFS and the case when the separation minimum is 0s, it is found that these are 76,282.24 kg and 69,066.73 kg, respectively. As expected, the performance metric for FCFS is higher (thus worse) than for the case when there is no separation minimum.

9.2.2 DPTA-BS

Several examples for the working of DPTA-BS have already been discussed in subsection 7.4.3. To complete the verification of the algorithm, and in particular its reliance on FCFS as last line of defence, here the results of the DPTA-BS algorithm will be discussed when comparing it to FCFS over one run. Firstly, this will be done for 360 aircraft, with D_{thres} set to 1000, and $(\alpha^-, \alpha^+) = (0.1, 0.9)$. The choice for D_{thres} may seem odd at first, but it ensures that the DPTA-BS algorithm never is triggered, and should rely on FCFS as last line of defence. Therefore, the results of the FCFS case and this DPTA-BS case should be identical. The plots of the inter-arrival times for identical scenarios can be found in Figure 9.3.



(a) (b)

Figure 9.3: Plots of inter-arrival times of a single run of 360 aircraft (this corresponds to a utilization level of 100%). In Figure 9.3a the plot is given for the DPTA-BS algorithm; In Figure 9.3b the same plot is given for FCFS.

It can be seen in Figure 9.3 that the minimal inter-arrival time of this DPTA-BS ($D_{thres} = 1000$) is 60s, which is identical to that of the pure FCFS. Further, the two figures, as well as the obtained results for the total costs are identical. This indicates the correct implementation of FCFS in DPTA-BS.

In addition to the implementation of FCFS in DPTA-BS it is necessary to verify that the performance of DPTA-BS is worse, or at most equal to, to that of the theoretically best attainable performance within the context of this research. As discussed before, the infinite capacity case, i.e. the case where there are no separation minima between aircraft, can be seen as this theoretical limit.

To verify this statement use has been made of a two-sample t-test for equal means without assuming equal variances for the two datasets. The two datasets are both for 75%

of capacity where one dataset is the result for DPTA-BS and the other for the infinite capacity case. The sample means of performance figures of the datasets are 70,618.36 kg and 69,117.42 kg, with the highest value corresponding to DPTA-BS.

It appeared from the two-sample t-test with a 5% significance level that there is no evidence to believe that the two datasets have the same mean (H_0 is rejected with a p-level of 1.5×10^{-150}), which means that it can be stated that the difference between the means is significant. As the average of the performance figures for DPTA-BS is higher than that for the infinite capacity case (i.e. DPTA-BS performs worse) it can be said that DPTA-BS falls below the upper limit of performance.

9.2.3 Assumed Runway Capacity

As stated in subsection 8.1.1 the assumption that the capacity at the metering fix is 60 ac/hr is not in line with real world operations. In reality this is in the order of 40 ac/hr. To see whether this assumption has an impact on the results the simulations will be repeated for both FCFS, RBS and DPTA-BS at a capacity of 30 ac/hr and a utilization level of 90% of capacity. The results can be found in Table 9.1.

Table 9.1: Results for FCFS, RBS and DPTA-BS under different values for C at a utilization level of 90% of capacity. $D_{thres} = 2$, $(\alpha^+, \alpha^-) = (0.1, 0.9)$ and $\tau_s = 30$ min.

	$\overline{CF_C = 30}$	$\overline{CF_C = 60}$
FCFS	$73,525 \pm 80.4$	$72,496 \pm 54.4$
RBS	$73,471 \pm 81.0$	$73,455 \pm 54.2$
DPTA-BS	$72,125 \pm 79.8$	$71,103 \pm 54.1$

It can be seen in Table 9.1 that the found $\overline{CF}$ are lower at $C = 60$. The difference is however staying roughly the same. This means that, even though the found performance under the assumed C will be better than for a realistic one, the difference is constant for the different assessed metrics. It is also observed that the standard error for $C = 30$ is higher than for $C = 60$. This is because fewer aircraft are simulated in the $C = 30$ cases as the stated capacity is halved, and the amount of simulations K stayed the same.

Chapter 10

Conclusions

Following the findings of the preceding chapters this chapter will provide a summary of what has been done in the research and a conclusion of what its findings are. This will be done in section 10.1. Additionally, in section 10.2 the results will be viewed from an academic perspective w.r.t. the literature study of chapter 2.

10.1 Conclusions

As stated in section 3.2 the main research to be answered in this research was *"How can the efficiency, measured in economic terms as resultant of unnecessary delays and fuel usage, of flights be improved by dynamically controlling the CTA time windows of arriving flights until the initial approach fix, and what is the effect on efficiency?"*. This question was answered in several steps.

The first part of the question was treated in chapter 7. In this chapter DPTA-BS was developed based around the usage of dynamic CTA windows. It was assumed that the error in wind speed is the primary source of uncertainty (for the airborne portion of the flight) in the usage of CTAs for arrival planning.

To evaluate the performance of the newly developed scheduling algorithm a new testing method had to be developed that was able to assess schedulers from a direct cost perspective. To this end a cost function was developed that took into account the cost of delay and the cost of fuel.

Based on the new testing methodology a sensitivity study of the setting parameters of the newly developed scheduling algorithm was performed. Based on this analysis a suitable set of setting parameters for DPTA-BS was established. This set of parameters was used in the further assessment of DPTA-BS.

To evaluate the performance of DPTA-BS in an operational context the amount of aircraft per distance in the simulation was varied to resemble a differing utilization of the runway capacity. It was found, as expected, that as the amount of aircraft per time unit approaches 100% of the runway capacity the performance of FCFS deteriorates considerably. It was also found that DPTA-BS performs significantly better than FCFS under these higher arrival loads. In situations where a lower percentage of the capacity is utilized the performance increase of DPTA-BS decreases, to a level for which no statistical evidence can be found that the performance is dissimilar to FCFS. This means that it can be concluded that at lower throughput levels DPTA-BS behaves similarly to FCFS and RBS.

To further elaborate on the performance of DPTA-BS Ration-by-Schedule was implemented in the same testing methodology. It was found that RBS performs better than FCFS, but considerably worse than DPTA-BS. It was found that part of the performance gain in DPTA-BS w.r.t. FCFS and RBS must be resulting from the fact that it is run on a regular basis over a large horizon.

Based on these conclusions the main research question has been answered. It was shown that the developed DPTA-BS scheduling algorithm that makes use of dynamic CTA time windows has a better efficiency (in economic terms) than FCFS and RBS. This is particularly true for situations where the actual utilization is close to capacity. The increase in efficiency depends on this level of utilization.

10.2 Academic Contribution

The most important contribution in academic terms is the fact that the research question is positively answered as it was concluded and shown that the usage of dynamic RTA windows can increase the efficiency of an arrival scheduler in economic terms on a broad scale. An algorithm that makes use of these windows has been developed and was shown to have a considerable increase in efficiency over FCFS.

A second contribution is the development of a new testing methodology for arrival schedulers. This new method is based around a cost function that takes into account the costs of fuel and delays, and their interrelation through the Cost Index. It also has a module for errors in wind predictions. This model and cost function can be used in other researches where it is desired to assess arrival schedulers in terms of direct costs for airlines.

Chapter 11

Recommendations

It was found that the newly developed DPTA-BS can considerably outperform both FCFS and RBS in economic terms. The performed research was however done in the limited context for a single runway and a single aircraft type (homogeneous set of aircraft). To prepare DPTA-BS for a future real-world implementation it is necessary to evaluate its performance in a case with multiple runways and for a non-homogeneous set of aircraft. It is also recommended to investigate the use of DPTA-BS in the context of 4D-trajectories as proposed by Klooster et al. in [3].

In addition it is necessary to understand that a scheduling technique is essentially a way of dealing with competing requests: Aircraft that are approaching an airfield all have the same request as they want to land as soon as possible. In principle all aircraft have to be treated equally to not favour one type of flight or airline at the cost of another. This principle brought birth to the notion of equitability: A scheme that has high equitability treats incoming requests 'fairly' and does not unfairly prioritize a certain type of flight or aircraft. Equitability is a returning topic in papers on scheduling techniques ([9], [10] and [39] being examples of some). Given the relative complexity of having to ensure equitability in a new scheme that intends to improve scheduling, a notion that is supported by Ball et al. in [10] where they introduce a way to explicitly design for equity, it was not taken into account in this research. It is nevertheless a greatly important topic to investigate were the concept to be made ready for real-world implementation. Therefore, it is necessary to investigate the equitability aspect of the developed DPTA-BS algorithm.

In addition to the mentioned academic recommendations a recommendation will be done for if DPTA-BS were to be implemented. If it were to be shown that DPTA-BS performs well in a multiple runway environment for a non-homogeneous set of aircraft, and if it is shown to do so equitably, there are other burdens to its implementation. This burden primarily originates from a trade-off of costs and benefits: DPTA-BS aims to reduce (average) direct costs for airlines, but to implement it an investment is necessary from airlines. They will need to invest financial resources before any gain from DPTA-BS can be attained. In fact, it is expected that a considerable portion of aircraft will be required to be able to adhere to DPTA-BS before a gain is attained. This will lead to a chicken or the egg dilemma as airlines will not be willing to make an investment before a cost reduction can be achieved, but a cost reduction won't be achieved until airlines have made an investment to implement it. It is therefore necessary to also research how many aircraft need to be able to be using DPTA-BS before a significant cost reduction can be attained. This also requires the development of a hybrid form of DPTA-BS wherein both DPTA-BS-able and DPTA-BS-unable aircraft are accounted for.

In addition, a consideration has to be made in terms of ATCo workload. It is possible that the employment of the proposed scheduling methodology puts higher pressure on ATCo's in certain situations. It is therefore necessary to study this effect.

Bibliography

[1] M O Ball and G Lulli. Ground Delay Programs : Optimizing over the Included Flight Set Based on Distance. *Air Traffic Control Quarterly*, 12(1):1–25, 2004.

[2] M Tielrooij, C Borst, M M Van Paassen, and M Mulder. Predicting Arrival Time Uncertainty from Actual Flight Information. *11th USA/Europe Air Traffic Management Research and Development Seminar*, 11(January), 2015.

[3] Joel Klooster, Keith Wichman, and Okko Bleeker. 4D Trajectory and Time-of-Arrival Control to Enable Continuous Descent Arrivals. In *AIAA Guidance, Navigation, and Control Conference*, number August, pages 1–17, 2008.

[4] Mihaela Mitici. Flexible Air Traffic Scheduling. Technical Report July, Universiteit van Amsterdam, NLR, 2011.

[5] Canso and The Boeing Company. Accelerating Air Traffic Management Efficiency: A Call to Industry. 2012.

[6] David De Smedt and Gerhard Berz. Study of the required time of arrival function of current FMS in an ATM context. In *26th Digital Avionics Systems Conference*, pages 1–10, 2007.

[7] Keith Wichman, Göran Carlsson, and Lars Lindberg. Flight Trials: "Runway-to-Runway" Required Time of Arrival Evaluations for Time-Based ATM Environment - Final Results. In *AIAA Guidance, Navigation, and Control Conference and Exhibit*, number August, 2002.

[8] Mahesh Balakrishna, Thomas A Becher, Paul V Macwilliams, The Mitre Corporation, Joel K Klooster, Wyatt D Kuiper, Patrick J Smith, G E Aviation Systems, and Grand Rapids. Seattle Required Time-of-Arrival Flight Trials Human-in-the-Loop Simulations. In *30th Digital Avionics Systems Conference*, pages 1–10, 2011.

[9] Al Secen. Evolution of First Come, First Serve to Best Capable, Best Served. In *Integrated Communications Navigations and Surveilance (INCNS) Conference*, Rockville, MD, 2013.

[10] Michael Ball, Robert Hoffman, and Avijit Mukherjee. Ground Delay Program Planning Under Uncertainty Based on the Ration-by-Distance Principle. *Transportation Science*, 41(4):444–456, 2010.

[11] J E Beasley, M Krishnamoorthy, Y M Sharaiha, and A Abramson. Scheduling Aircraft Landings The Static Case. pages 180–197, 2000.

[12] Peter Brucker. *Scheduling Algorithms.* Springer, 2001.

[13] Mohammad Mesgarpour, Chris N Potts, and Julia A Bennell. Models for Aircraft Landing Optimization. pages 1–4, 2010.

[14] Luis Delgado and Xavier Prats. Fuel consumption assessment for speed variation concepts during the cruise phase. pages 1–12, 2009.

[15] Luis Delgado and Xavier Prats. An en-route speed reduction concept for absorbing air traffic flow management delays. *Journal of Aircraft*, 49(1):214–224, 2012.

[16] Aslaug Haraldsdottir, Julien Scharl, Janet King, Ewald Schoemig, and Matthew Berge. Analysis of Arrival Management Performance with Aircraft Required Time of Arrival Capabilities. *The 26th Congress of ICAS and 8th AIAA ATIO*, (September):1–10, 2008.

[17] Fan Han, B L William Wong, and Stephen Gaukrodger. Improving future air traffic punctuality : pinch-and-pull target windows. 4:207–216, 2010.

[18] Kostas Margellos, Student Member, and John Lygeros. Toward 4-D Trajectory Management in Air Traffic Control : A Study Based on Monte Carlo Simulation and Reachability Analysis. 21(5):1820–1833, 2013.

[19] Pilot Salaries. *http://www.airliners.net/aviation-forums/general_aviation/read.main/40840/*, 1999.

[20] How many cabin crew on Boeing 777? *http://www.airliners.net/aviation-forums/general_aviation/read.main/2170948/*, 2005.

[21] Salary.com. Flight Attendant Salaries. *http://www1.salary.com/Flight-Attendant-Salary.html*, 2016.

[22] SeekingAlpha.com. Does A $7 Million Boeing 777-200ER Compare To A Brand New Dreamliner? (Part 2). *http://seekingalpha.com/article/3958785-7-million-boeing-777minus-200er-compare-brand-new-dreamliner-part-2*, 2016.

[23] Average Daily Flying Time. *http://www.airliners.net/aviation-forums/general_aviation/read.main/492074/*, 2001.

[24] NASA. Forces on Aircraft. *http://quest.nasa.gov/aero/teachers/foa.html.*

[25] R Howe-Veenstra. *Commercial Aircraft Trajectory Optimization and Efficiency of Air Traffic Control Procedures.* PhD thesis, 2011.

[26] John D Anderson. *Introduction to Flight.* 2008.

[27] Antonio A. Trani. Analysis of Air Transportation Systems Fundamentals of Aircraft Performance (2), 2010.

[28] John D Anderson. *Aircraft Performance and Design.* McGraw Hill, 1999.

[29] Getting to Grips with the Cost Index. Cost Index, 1998.

[30] Emilien Robert and David De Smedt. Comparison of operational wind forecasts with recorded flight data. *Tenth USA/Europe Air Traffic Management Research and Development Seminar*, 2013.

[31] A.W. Zhu and P Haltion. Climatology & Weather Forecasting A Method for Improving the Accuracy of Weather Forecasts Based on a Comprehensive Statistical Analysis of Historical Data for the Contiguous United States. 2(1):1–9, 2014.

[32] Clayton Tino. *Wind Models and Stochastic Programming Algorithms for En Route Trajectory Prediction and Control*. PhD thesis, 2013.

[33] National Oceanic & Atmospheric Administration (NOAA). Rapid Refresh (RAP). *http://rapidrefresh.noaa.gov/*, 2016.

[34] F M Robasky, R A DeLaura, R F Ferris, S W Troxel, and N K Underhill. Initial Assessment of Wind Forecasts for Airport Acceptance Rate (AAR) and Ground Delay Program (GDP) Planning. 2014.

[35] Jesper Bronsvoort. *Improved Ground-Based Trajectory Prediction for Air Traffic Management*. PhD thesis, 2011.

[36] U.S. Department of Transportation. *Order JO 7110.65W*. 2015.

[37] Stefan Kern and Michael Schultz. Development of a generic airport for determining runway capacity. pages 1–10, 2015.

[38] Aslaug Haraldsdottir, Julien Scharl, Matthew E Berge, Ewald G Schoemig, and Michael L Coats. Arrival Management with Required Navigation Performance and 3D Paths. In *USA/Europe Air Traffic Management Research and Development Seminar*, pages 1–12, 2007.

[39] Chris Brinton, Stephen Atkins, Lara Cook, Steven Lent, and Tom Prevost. Ration by schedule for airport arrival and departure planning and scheduling. *2010 Integrated Communications, Navigation, and Surveillance Conference Proceedings, ICNS 2010*, pages 1–9, 2010.

[40] The Mitre Corporation. Verification and Validation of Simulation Models.

[41] Hanbong Lee and Hamsa Balakrishnan. A Study of Tradeoffs in Scheduling Terminal-Area Operations. *Proceedings of the IEEE*, (December 2008):2081 – 2095, 2008.

[42] René Verbeek, Dries Visser, and Richard Curran. Probabilistic Arrival Planning Making Use of Dynamic Arrival Windows, ATO MSc Assignment, 2015.

Appendix A

Numerical Results

Table A.1: Full numerical results of Figure 8.1: the performance of DPTA-BS, FCFS and RBS under utilization levels. (1)

	25%	30%	35%	40%	45%	50%
FCFS mean [kg]	70383.71	70465.67	70479.82	70502.04	70517.3	70516.23
FCFS std [kg]	5351.21	4883.38	4680.12	4265.88	4058.9	3955.75
RBS mean [kg]	70367.75	70462.4	70472.86	70452.45	70449.59	70462.78
RBS std [kg]	5456.08	4874.89	4690.52	4306.87	4021.76	3906.24
DPTA-BS mean [kg]	70367.81	70469.09	70473.79	70446.37	70441.616	70419.5443
DPTA-BS std [kg]	5481.45	4870.83	4742.61	4267.29	4097.95	3874.78

Table A.2: Full numerical results of Figure 8.1: the performance of DPTA-BS, FCFS and RBS under utilization levels. (2)

	55%	60%	65%	70%	75%	80%
FCFS mean [kg]	70527.11	70673.22	70846.1	70873.72	71007.69	71259.91
FCFS std [kg]	3639.69	3578.57	3426.1	3351.04	3268.99	3116.23
RBS mean [kg]	70435.83	70581.06	70677.75	70684.02	70722.35	71030.81
RBS std [kg]	3714.67	3540.37	3346.94	3367.68	3226.59	3078.3
DPTA-BS mean [kg]	70381.2733	70542.71	70639.6365	70669.08	70694.34	70711.87
DPTA-BS std [kg]	3646.16	3549.47	3461.84	3369.95	3246.46	3061.58

Table A.3: Full numerical results of Figure 8.1: the performance of DPTA-BS, FCFS and RBS under utilization levels. (3)

	85%	90%	95%	100%
FCFS mean [kg]	71691.33	72446.31	73869.32	76375.6
FCFS std [kg]	3074.74	2910.52	2817.57	2588.67
RBS mean [kg]	71394.01	72135.36	73596.91	75990.34
RBS std [kg]	3088.43	2916.88	2808.78	2607.21
DPTA-BS mean [kg]	70771.94	70905.83	71083.41	71379.33
DPTA-BS std [kg]	3030.58	2932.99	2802.9	2785.16

Table A.4: Full Numerical results of Figure 8.3a: the performance of DPTA-BS for differing D_{thres} as well as RBS and FCFS at 50% of capacity. (1)

	Indep.	1	1.5	2	2.5
Mean FCFS [kg]	70532.3				
std FCFS [kg]	3895.42				
Mean RBS [kg]	70462.8				
std RBS [kg]	3906.24				
Mean DPTA-BS [kg]		70510.55	70493.71	70441.01	70414.01
std DPTA-BS [kg]		3911.57	3879.59	3920.27	3891.53

Table A.5: Full Numerical results of Figure 8.3a: the performance of DPTA-BS for differing D_{thres} as well as RBS and FCFS at 50% of capacity. (2)

	Indep.	3	3.5	4	4.5	5
Mean FCFS [kg]	70532.3					
std FCFS [kg]	3895.42					
Mean RBS [kg]	70462.8					
std RBS [kg]	3906.24					
Mean DPTA-BS [kg]		70453.11	70467.89	70469.78	70468.28	70468.84
std DPTA-BS [kg]		3887.99	3876.03	3867.96	3831.53	3859.63

Table A.6: Full Numerical results of Figure 8.3b: the performance of DPTA-BS for differing D_{thres} as well as RBS and FCFS at 75% of capacity. (1)

	Indep.	1	1.5	2	2.5
Mean FCFS [kg]	70992.7				
std FCFS [kg]	3283.86				
Mean RBS [kg]	70722.3				
std RBS [kg]	3226.57				
Mean DPTA-BS [kg]		70610.55	70599.47	70591.42	70593.23
std DPTA-BS [kg]		3211.57	3214.17	3189.76	3196.7

Table A.7: Full Numerical results of Figure 8.3b: the performance of DPTA-BS for differing D_{thres} as well as RBS and FCFS at 75% of capacity. (2)

	Indep.	3	3.5	4	4.5	5
Mean FCFS [kg]	70992.7					
std FCFS [kg]	3283.86					
Mean RBS [kg]	70722.3					
std RBS [kg]	3226.57					
Mean DPTA-BS [kg]		70608.53	70615.29	70643.05	70674.17	70687.04
std DPTA-BS [kg]		3223.64	3242.53	3234.78	3211.88	3231.61

Table A.8: Full Numerical results of Figure 8.3c: the performance of DPTA-BS for differing D_{thres} as well as RBS and FCFS at 90% of capacity. (1)

	Indep.	1	1.5	2	2.5	3
Mean FCFS [kg]	72446.31					
std FCFS [kg]	2873.95					
Mean RBS [kg]	72124.19					
std RBS [kg]	2868.49					
Mean DPTA-BS [kg]		70924.88	70916.38	70901.46	70907.78	70942.36
std DPTA-BS [kg]		2818.54	2829.96	2874.91	2837.47	2866.51

Table A.9: Full Numerical results of Figure 8.3c: the performance of DPTA-BS for differing D_{thres} as well as RBS and FCFS at 90% of capacity. (2)

	Indep.	3.5	4	4.5	5
Mean FCFS [kg]	72446.31				
std FCFS [kg]	2873.95				
Mean RBS [kg]	72124.19				
std RBS [kg]	2868.49				
Mean DPTA-BS [kg]		70955.82	70983.5	71010.1	71048.94
std DPTA-BS [kg]		2821.88	2841.94	2849.02	2838.42

Table A.10: Full Numerical results of Figure 8.3d: the performance of DPTA-BS for differing D_{thres} as well as RBS and FCFS at 95% of capacity. (1)

	Indep	1	1.5	2	2.5	3
Mean FCFS [kg]	73828.83					
std FCFS [kg]	2814.67					
Mean RBS [kg]	73594.14					
std RBS [kg]	2821.35					
Mean DPTA-BS [kg]		71108.47	71098.81	71074.62	71089.06	71093.92
std DPTA-BS [kg]		2788.48	2792.49	2807.37	2865.54	2804.11

Table A.11: Full Numerical results of Figure 8.3d: the performance of DPTA-BS for differing D_{thres} as well as RBS and FCFS at 95% of capacity. (2)

	Indep	3.5	4	4.5	5
Mean FCFS [kg]	73828.83				
std FCFS [kg]	2814.67				
Mean RBS [kg]	73594.14				
std RBS [kg]	2821.35				
Mean DPTA-BS [kg]		71119.19	71158.89	71217.03	71283.02
std DPTA-BS [kg]		2819.5	2808.22	2818.72	2800.16

Table A.12: Full Numerical results of Figure 8.4a: the performance of DPTA-BS for differing τ_s as well as RBS and FCFS at 50% of capacity.

	Indep.	10	20	30	60	120	180	240	300
FCFS [kg]	70532								
FCFS [kg] std	3895								
RBS [kg]	70462								
RBS [kg] std	3906								
DPTA-BS		70433	70430	70419	70435	70471	70483	70498	70513
DPTA-BS std		3853	3832	3883	3917	3912	3881	3872	3827

Table A.13: Full Numerical results of Figure 8.4b: the performance of DPTA-BS for differing τ_s as well as RBS and FCFS at 75% of capacity.

	Indep.	10	20	30	60	120	180	240	300
FCFS [kg]	71008								
FCFS [kg] std	3269								
RBS [kg]	70722								
RBS [kg] std	3227								
DPTA-BS		70639	70639	70648	70644	70672	70683	70705	70719
DPTA-BS std		3217	3238	3232	3218	3244	3236	3260	3230

Table A.14: Full Numerical results of Figure 8.4c: the performance of DPTA-BS for differing τ_s as well as RBS and FCFS at 90% of capacity.

	Indep.	10	20	30	60	120	180	240	300
FCFS [kg]	72446								
FCFS [kg] std	2910								
RBS [kg]	72135								
RBS [kg] std	2916								
DPTA-BS		70953	70968	70946	70953	70966	71149	71363	71751
DPTA-BS std		2853	2896	2875	2863	2845	2817	2839	2837

Table A.15: Full Numerical results of Figure 8.4d: the performance of DPTA-BS for differing τ_s as well as RBS and FCFS at 95% of capacity.

	Indep.	10	20	30	60	120	180	240	300
FCFS [kg]	73869								
FCFS [kg] std	2818								
RBS [kg]	73597								
RBS [kg] std	2809								
DPTA-BS		71090	71093	71095	71101	71125	71329	71541	71978
DPTA-BS std		2797	2791	2781	2785	2792	2780	2791	2805

Table A.16: Full Numerical results of Figure 8.5a: the performance of DPTA-BS for differing α^- as well as RBS and FCFS at 50% of capacity. Having $\alpha^- = 0.1$ means that $\alpha^+ = 0.9$. The same holds for $\alpha^- = 0.2$ with $\alpha^+ = 0.8$, and $\alpha^- = 0.3$ with $\alpha^+ = 0.7$.

	Indep.	0.1	0.2	0.3
Mean FCFS [kg]	70516.23			
std FCFS [kg]	3955.75			
Mean RBS [kg]	70462.78			
std RBS [kg]	3906.24			
Mean DPTA-BS [kg]		70411.99	70416.1	70418.77
std DPTA-BS [kg]		3841.58	3891.58	3871.52

Table A.17: Full Numerical results of Figure 8.5b: the performance of DPTA-BS for differing α^- as well as RBS and FCFS at 75% of capacity. Having $\alpha^- = 0.1$ means that $\alpha^+ = 0.9$. The same holds for $\alpha^- = 0.2$ with $\alpha^+ = 0.8$, and $\alpha^- = 0.3$ with $\alpha^+ = 0.7$.

	Indep.	0.1	0.2	0.3
Mean FCFS [kg]	70992.7			
std FCFS [kg]	3283.86			
Mean RBS [kg]	70722.3			
std RBS [kg]	3226.57			
Mean DPTA-BS [kg]		70601.99	70611.1	70618.77
std DPTA-BS [kg]		2800.2	2864.04	2805.44

Table A.18: Full Numerical results of Figure 8.5c: the performance of DPTA-BS for differing α^- as well as RBS and FCFS at 90% of capacity. Having $\alpha^- = 0.1$ means that $\alpha^+ = 0.9$. The same holds for $\alpha^- = 0.2$ with $\alpha^+ = 0.8$, and $\alpha^- = 0.3$ with $\alpha^+ = 0.7$.

	Indep.	0.1	0.2	0.3
Mean FCFS [kg]	72446.31			
std FCFS [kg]	2910.52			
Mean RBS [kg]	72135.36			
std RBS [kg]	2916.88			
Mean DPTA-BS [kg]		70708.17	70906.1	70905.83
std DPTA-BS [kg]		2874.12	2837.39	2802.9

Table A.19: Full Numerical results of Figure 8.5d: the performance of DPTA-BS for differing α^- as well as RBS and FCFS at 95% of capacity. Having $\alpha^- = 0.1$ means that $\alpha^+ = 0.9$. The same holds for $\alpha^- = 0.2$ with $\alpha^+ = 0.8$, and $\alpha^- = 0.3$ with $\alpha^+ = 0.7$.

	Indep.	0.1	0.2	0.3
Mean FCFS [kg]	73869.32			
std FCFS [kg]	2817.57			
Mean RBS [kg]	73596.91			
std RBS [kg]	2808.78			
Mean DPTA-BS [kg]		71087.13	71081.53	71083.41
std DPTA-BS [kg]		2809.78	2819.57	2802.9

Appendix B

Thesis Assignment

The MSc Assginment is given in Figure B.1.

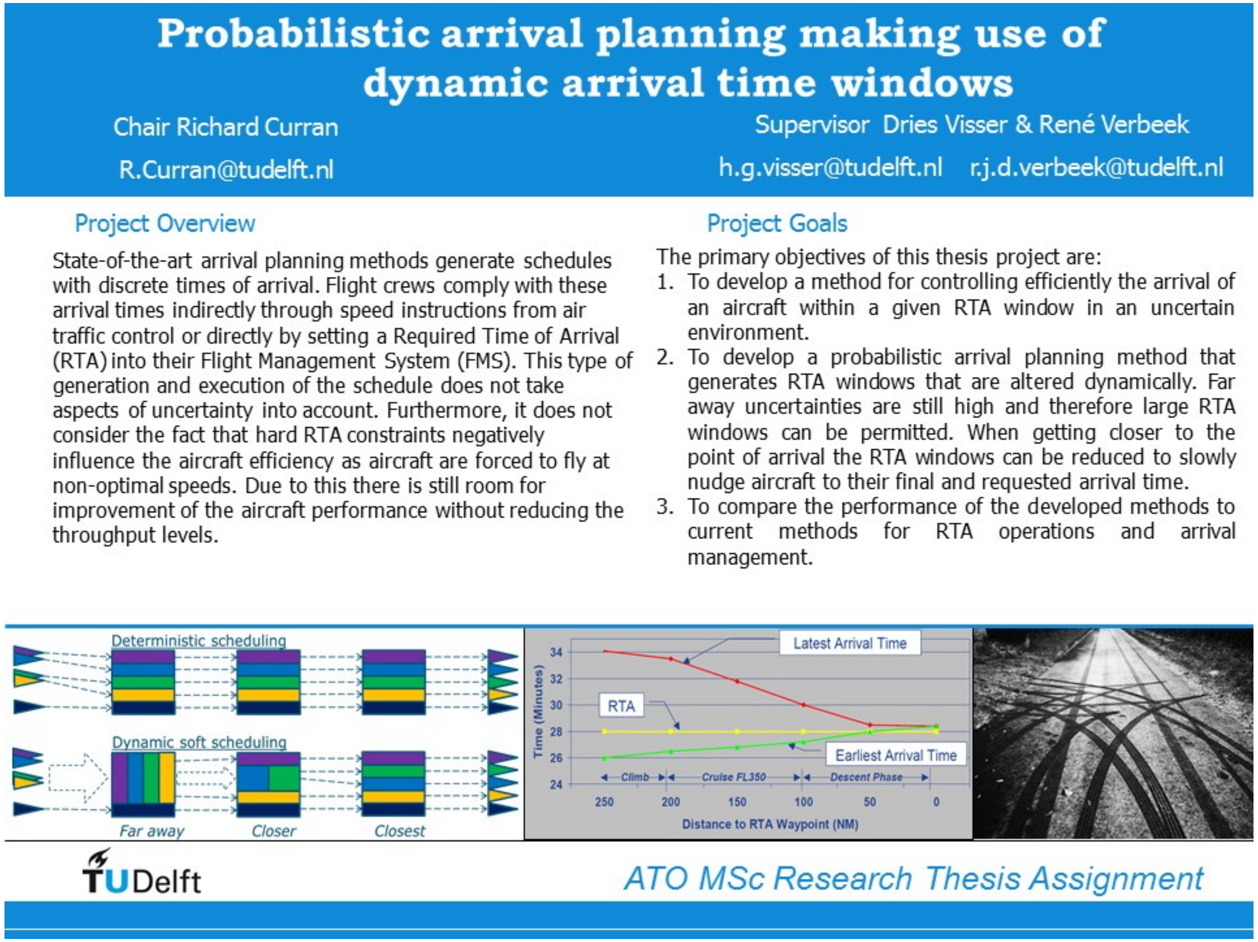


Figure B.1: MSc Graduation Assignment, [42]